Optoelectronic Information Processing

Integrity ★ Service ★ Excellence

7 MAR 2012

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NAME: Gernot S. Pomrenke

BRIEF DESCRIPTION OF PORTFOLIO:

Explore optoelectronic information processing, integrated photonics, and associated optical device components & fabrication for air and space platforms to transform AF capabilities in computing, communications, storage, sensing and surveillance … with focus on nanotechnology approaches. Explore chip-scale optical networks, signal processing, nanopower and terahertz radiation components. Explore light-matter interactions at the subwavelength- and nano-scale between metals, semiconductors, & insulators.

LIST SUB-AREAS IN PORTFOLIO:

- Integrated Photonics: Optical Components, Optical Buffer, Silicon Photonics
- Nanophotonics : (Plasmonics, Photonic Crystals, Metamaterials) & Nano-Probes & Novel Sensing
- Reconfigurable Photonics and Electronics (DCT)
- Nanofabrication, 3-D Assembly, Modeling & Simulation Tools
- Quantum Computing w/ Optical Methods
- Terahertz Sources & Detectors

Optoelectronic Information Processing

Nanophotonics, Plasmonics, Integrated & Silicon Photonics

MOTIVATION

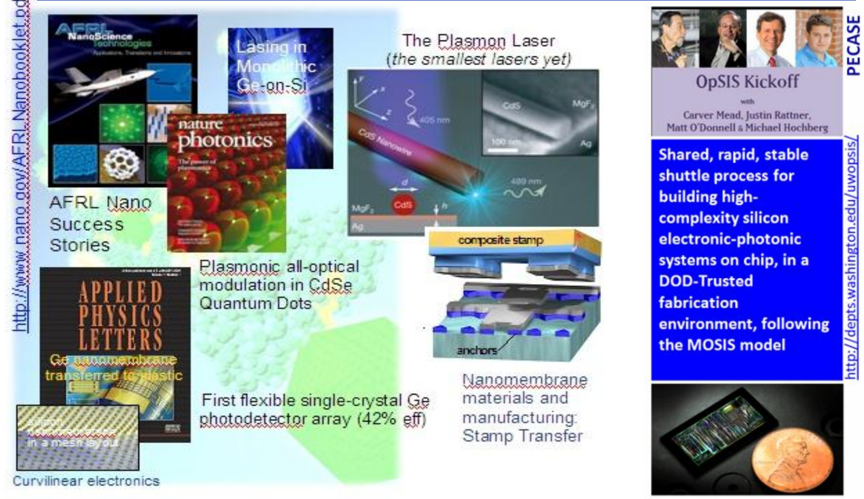
--Exploiting the nanoscale for photonics: nanostructures, plasmonics, metamaterials

--Overcoming current interconnect challenges

--Need for Design Tools for photonic IC's: scattered landscape of specialized tools

--Enable Novel Computing (Quantum Computing, All-Optical, Hybrid, HPC) & Ultra Low Power Devices

Engine for 21st Century Innovation – foundation for new IT disruptive technologies



SCIENTIFIC CHALLENGES

--Explore light-matter interactions at the subwavelength- and nano-scale between metals, semiconductors, & insulators

--Radiative lifetimes and gain dynamics

--E&M fields & strong nonlinearities

--Fundamental building block of information processing in the post-CMOS era

--Precise assembly & fabrication of hierarchical 3-D photonics

PAYOFF

--Exploit CMOS: Complex circuits structures benefit from chip-scale fabrication

--Fiber-optic comm. with redundancy at silicon cost for aerospace systems

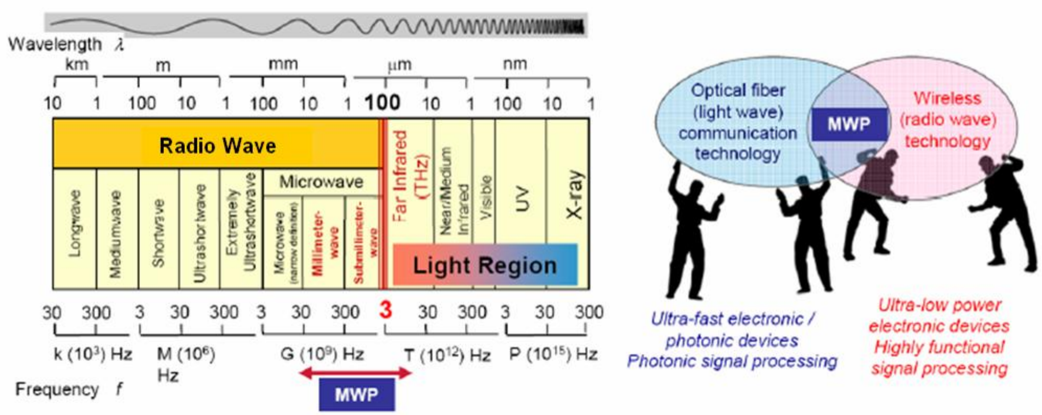
--Establish a shared, rapid, stable shuttle process

--Enable airborne C4ISR: combine SWaP benefits w/ best-in-class device performance

Transformational Opportunities

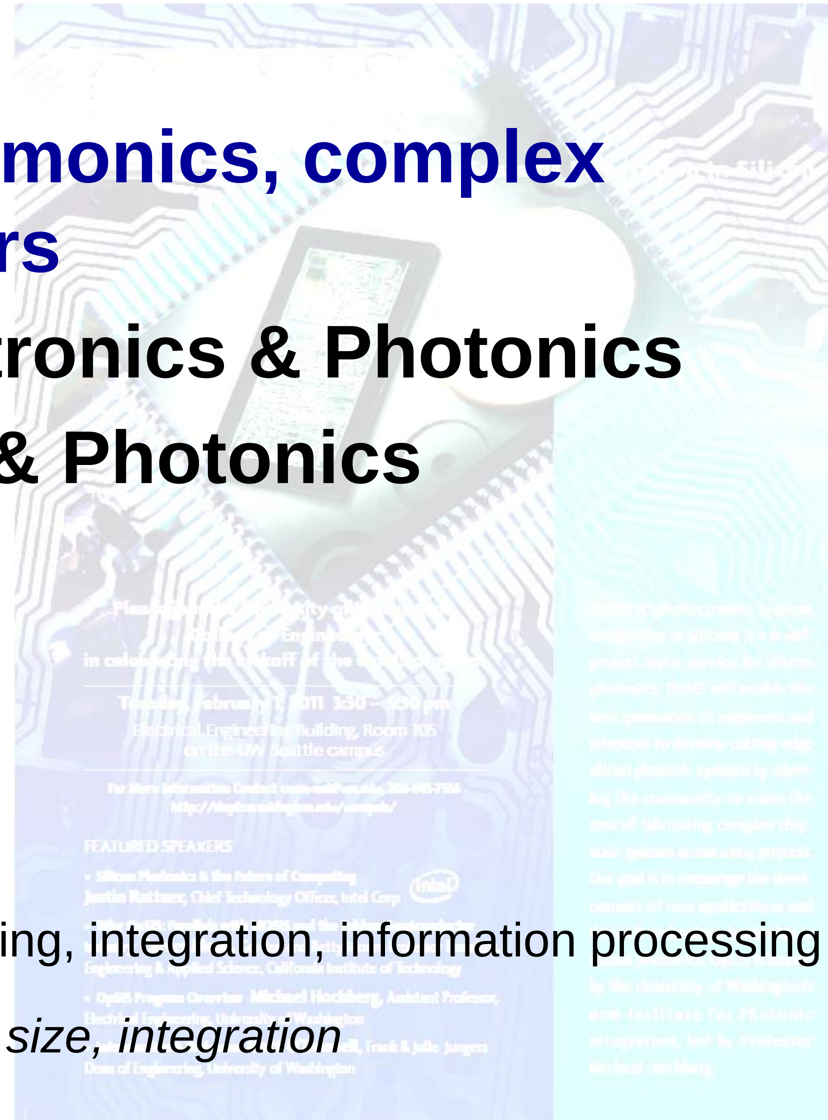
Reconfigurable chip-scale photonic – All optical switching on a chip; Multistage tunable wavelength converters and multiplexers; All optical push-pull converters; Optical FPGA; Compact beam steering; Very fine pointing, tracking, and stabilization control; Ultra-lightweight reconfigurable antennas

THz & Microwave/Millimeter Wave photonics, which merges radio-wave and photonics technologies: high-speed wireless comm., non-invasive & non-ionizing radiation sensors, spectroscopy and more effective in poor weather conditions.



Integrated photonics circuits – <u>Photonic On-Chip Network</u>, the promise of silicon photonics, electronics and photonics on the same chip (driver for innovation, economy, & avionics)

Outline/Agenda

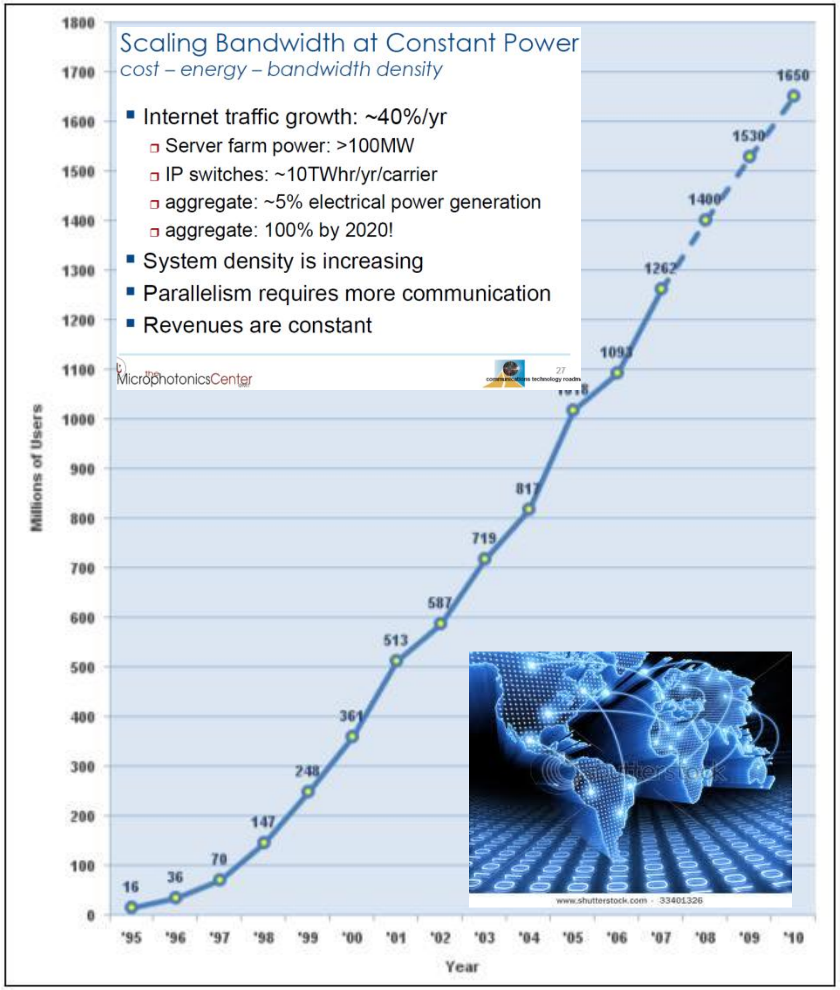


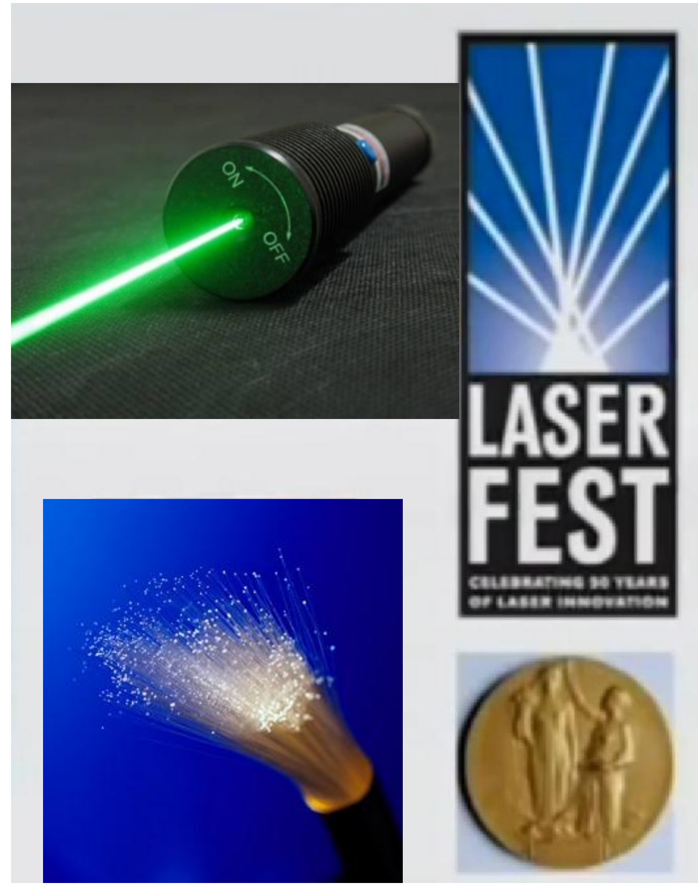
- **Nanophotonics: plasmonics, complex structures, nanolasers**
- **Reconfigurable Electronics & Photonics**
- **Nanomanufacturing & Photonics**
- **Quantum Computing**

Theme: nanophotonics, nanomanufacturing, integration, information processing

Speed, low power, size, integration

The Photonics Revolution





Cumulated growth Internet users in the world 1995-2010

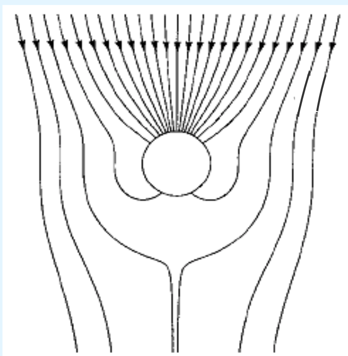
Faster, Smaller, Cheaper, less power
Follow Moore's Law
Stumbling Block to do this with light

Plasmonics: Manipulating Light at the Nanoscale with Metals

Basic optical properties of metallic nanostructures - Optics Meets Nanotechnology

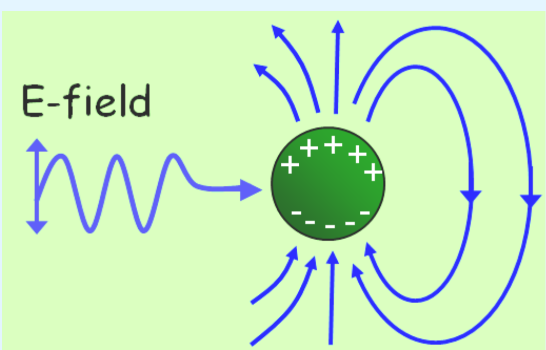
Particles can concentrate light

- **Light focusing by a 20 nm ∅ Aluminum particle**



C. F. Bohren, D. R. Huffman, Absorption and Scattering of Light by Small Particles, Wiley, New York 1983

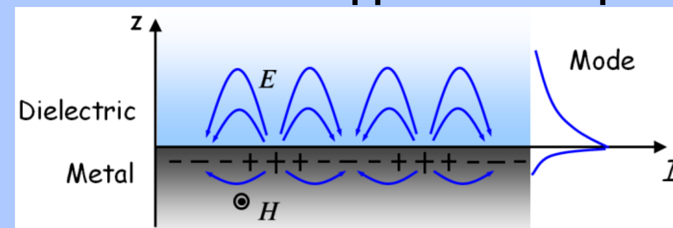
- **Explanation: Electron oscillations\plasmons**



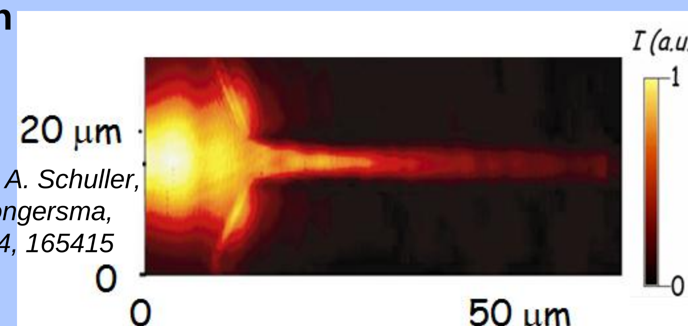
- **Metals enable nanoscale manipulation of light !**

Metal surfaces can guide light

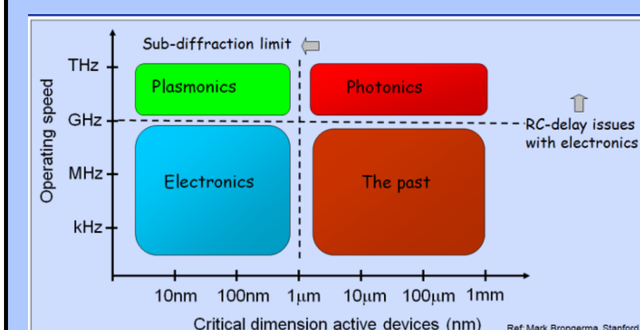
- **Metal surfaces support surface plasmons**



- **Near-field image of a propagating surface plasmon**



Rashid Zia, Jon A. Schuller, and Mark L. Brongersma, Phys. Rev. B, 74, 165415 (2006).



Plasmonics will enable synergy between electronics and photonics

Plasmonic Structures for CMOS Photonics and Control of Spontaneous Emission

P.I. Harry Atwater, Caltech (haa@caltech.edu)

Objective: Design and demonstrate plasmonic nanophotonic materials and structures for CMOS-compatible active switching and control of spontaneous emission

Approach: Exploit plasmonic phenomena that enable extreme light confinement and dramatic modification of local density of optical states to:

- *Achieve unprecedented refractive index modulation (Δn ~ 1)*
- *Create structures for ultra-compact photonic switching*
- *Enable >100x increase in spontaneous emission of semiconductor emitters*
- *Design ultralow loss plasmonic materials and plasmonic-photonic waveguide transitions*

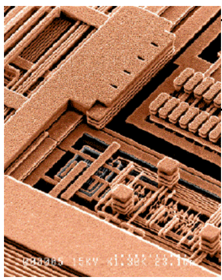
Impact: Nanophotonic materials and devices for:

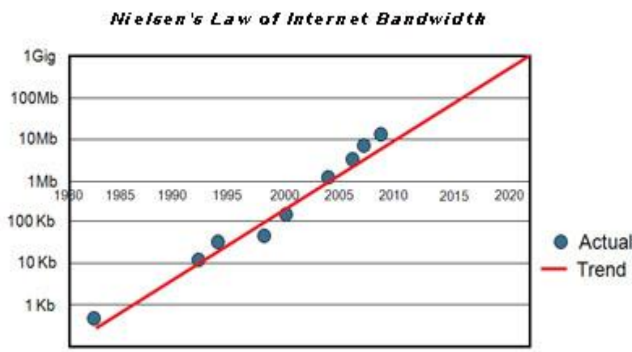
- *Ultra-compact low power optical and switching*
- *Efficient high speed modulation of spontaneous emission*

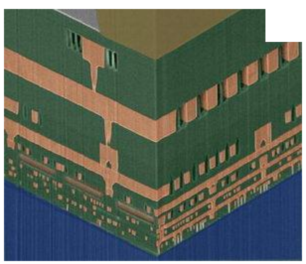
Relevance: Deliverables will lead to ultra-compact, robust and highly efficient photonic components and networks optimally suited for insertion into low-power mobile military information systems.

Plasmonic Photonic Information Systems

Today: information system use growing exponentially, but computing systems still limited by moving charge in interconnects

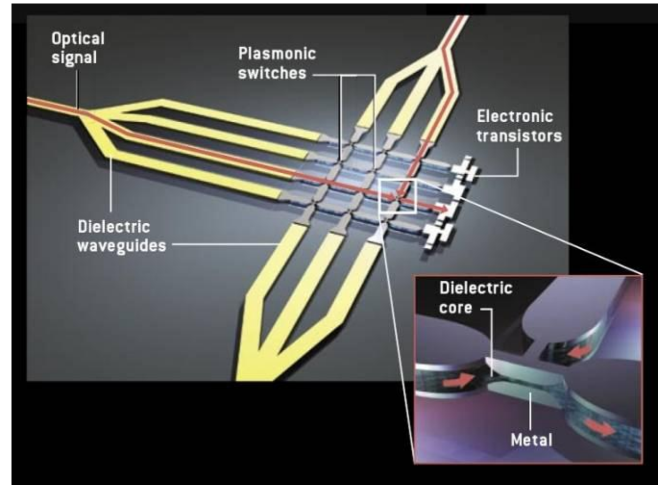






- ***5 km of wiring on 1 cm^2 chip***
- ***Transistors are fast: (f_t > 100 GHz), but processors are slow (1-3 GHz)***
- ***Power dissipation limited by charging capacitors on wire interconnects $P = ½ CV^2f$***

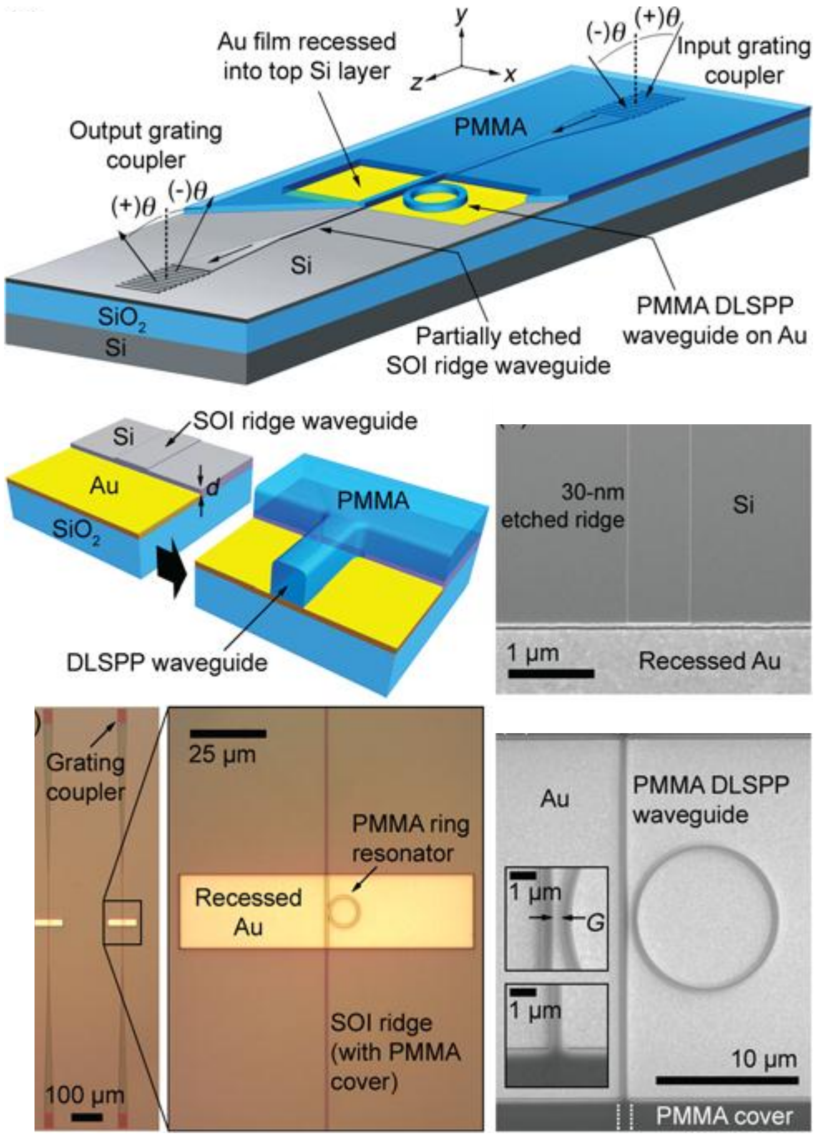
A plasmonic/photonic network approach to address the bottleneck:



- ***Treat photons at 1500 nm as a utility that comes from an off-chip cw laser via low-loss dielectric waveguides***
- ***Create ultracompact plasmonic electro-optic, all-optical and optomechanical switching elements and mechanisms***
- ***Develop ultralow loss (<1 dB/transition) plasmonic-photonic waveguide couplers interconnected at << λ scale***
- ***Design chip-based photonics networks of ultracompact low-power switches interconnect via low loss dielectric waveguides***

AFRL

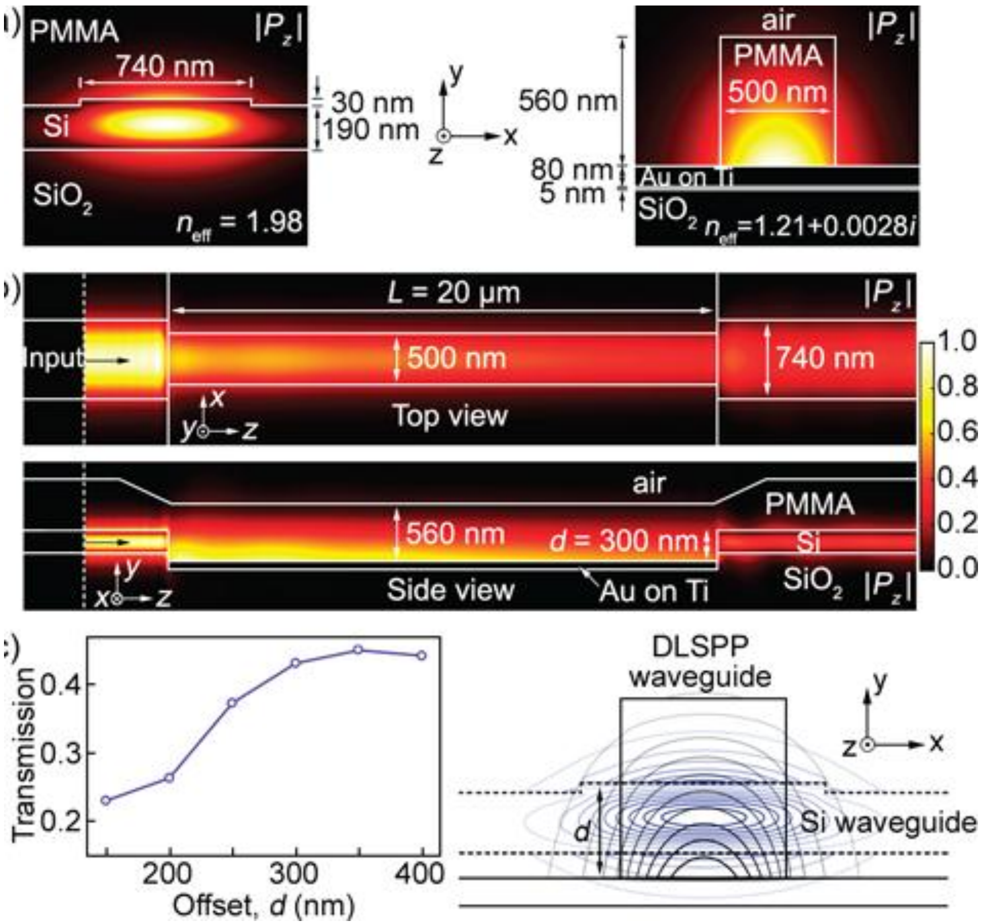
Ultralow (<1 dB) Coupling from SOI Waveguides to Plasmonic Waveguides



- TM mode photonic waveguide at 1500 nm
- Plasmonic waveguide: dielectrically-loaded surface plasmon waveguide (25 µm-long PMMA-on-Au stripes)
- 1.9 dB loss per coupler (in and out of Au section), or 0.95 dB per dielectric-to-plasmonic transition

R.M. Briggs, J. Grandidier, S.P. Burgos, E. Feigenbaum and HA Atwater *Nano Letters*, **10** 4851 (2010).

Ultralow (<1 dB) Coupling from SOI Waveguides to Plasmonic Waveguides



R.M. Briggs, J. Grandidier, S.P. Burgos, E. Feigenbaum and HA Atwater *Nano Letters*, **10** 4851 (2010).

Key to Success:

- Careful attention to mode-matching between SOI wavguide and plasmon waveguide
- Requires vertical offset between Si core and metallic stripe of surface plasmon waveguide for highest coupling efficiency
- Process is compatible with standard CMOS reactive ion etching – no complex 3D structures or adiabatic tapers required

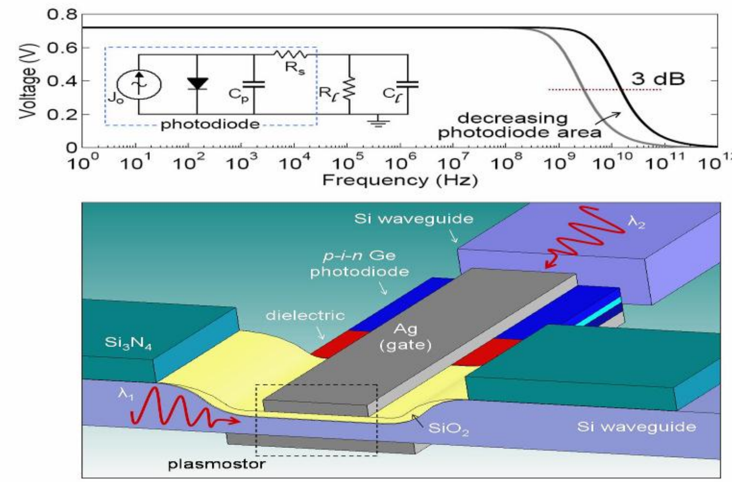
Unity-order refractive index modulation by field effect switching

Background:

In 2009, Atwater group demonstrated the 'plasMOStor', a CMOS field effect electro-optical switch at 1500 nm.

How it works:

- **Field effect control of carrier density in Si-core MIM plasmonic waveguide → refractive index modulation**
- **Switching via refractive index modulation of waveguide photonic mode near cut-off.**
- **Experimentally demonstrated switching >10dB on/off ratio in < 1 μm scale device with < 1 Volt applied bias**



J.A. Dionne, K.A. Diest and H.A. Atwater, Nano Letters, 8, 1506 (2009)

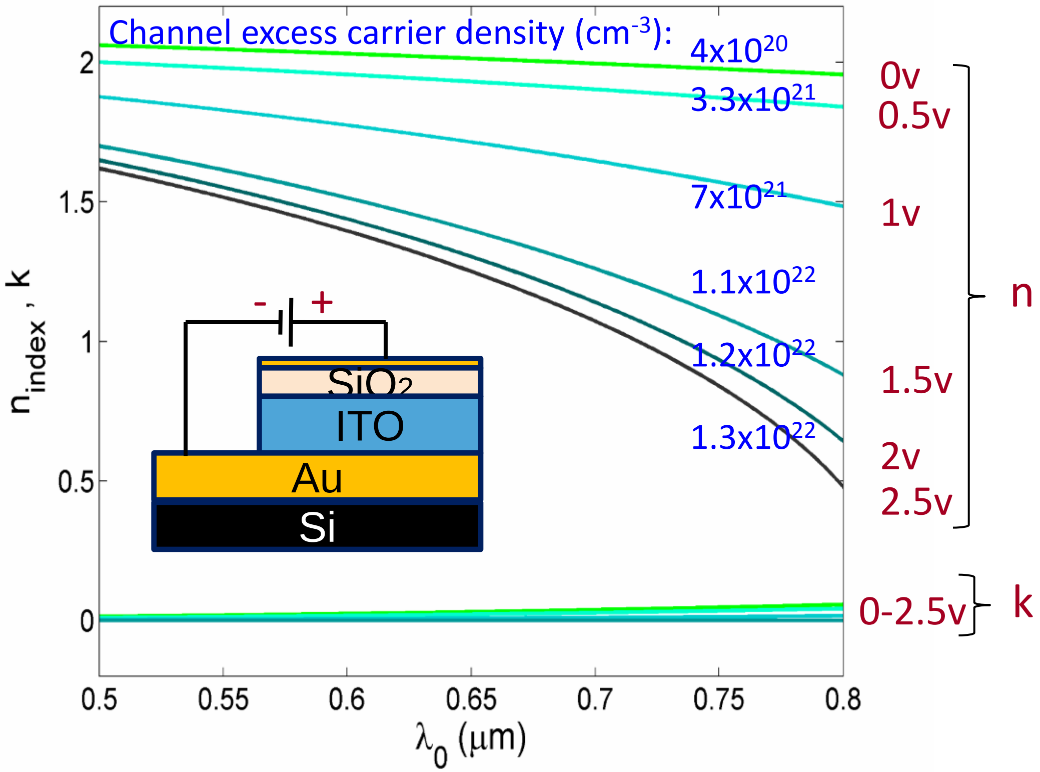
However, a challenge: *For Silicon and modulation of excess carrier density by $n' = 10^{19}cm^{-3}$, only produces a refractive index modulation* at λ=1.5μm → Δn_{index}~0.009…

Solution: *Enhance Δn_{index} to be ~1 by increasing Δn…*

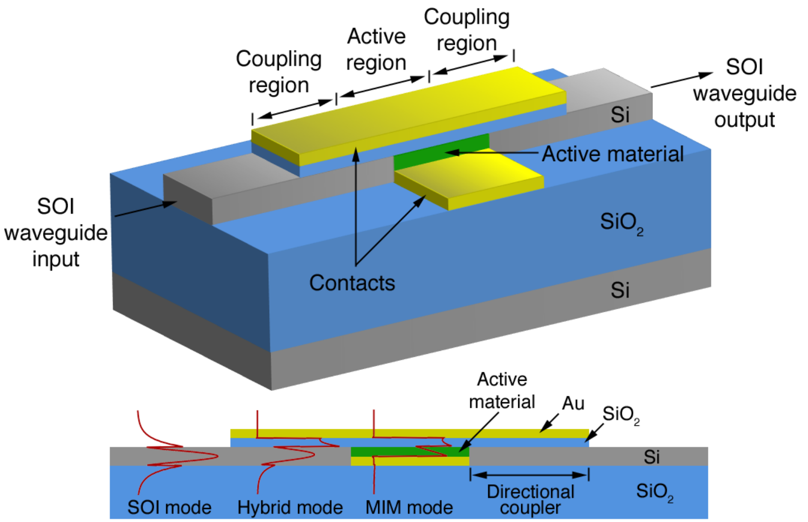
How to do it: *Use conducting oxide as the field effect channel material*

Unity-order refractive index modulation by field effect switching

Experiment:



Plasmonic Device Structure:



Local index change in ITO channel:

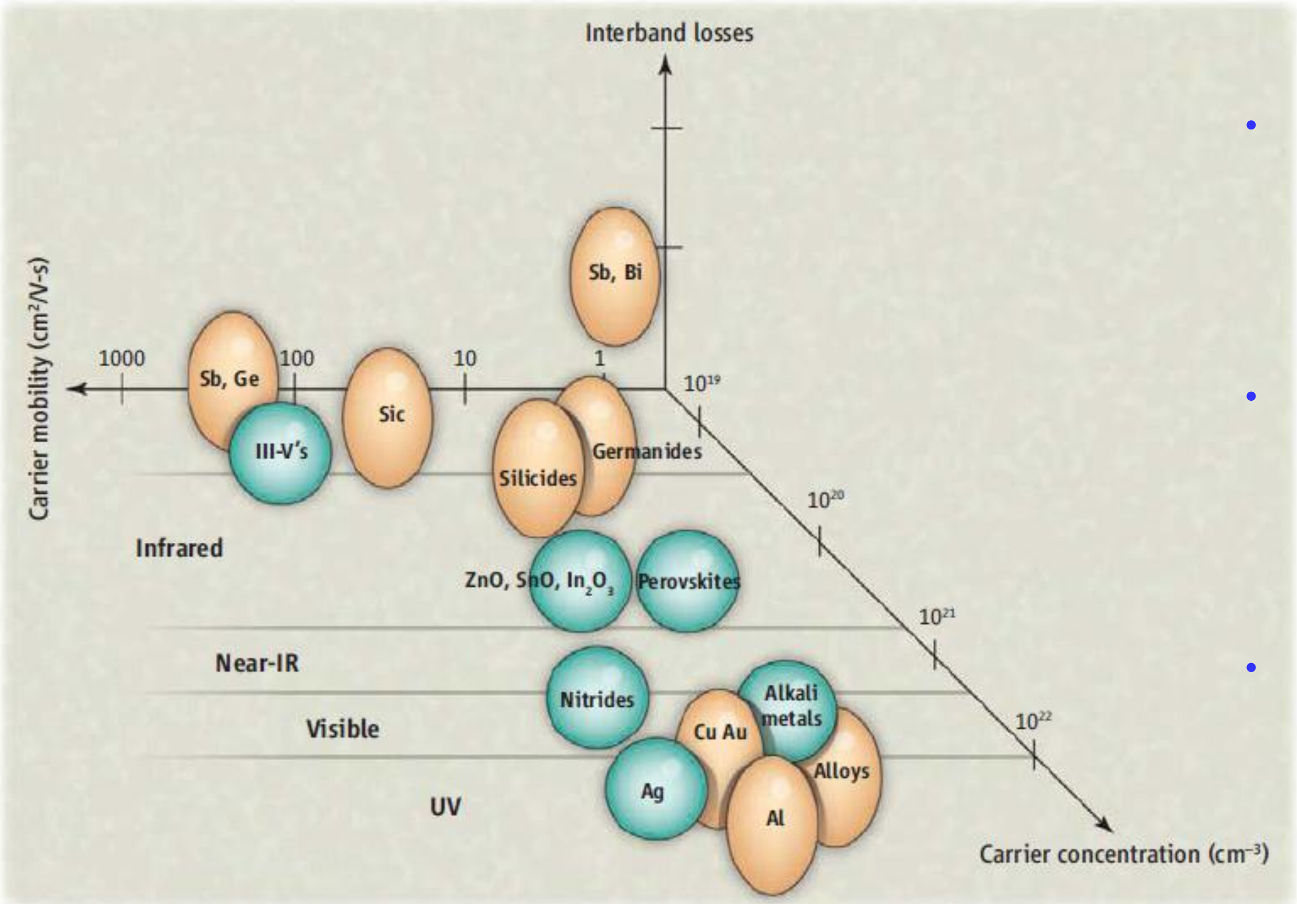
$\Delta n = 1.48$ at λ_0=800nm in 10 nm channel layer (from spectroscopic ellipsometry)

Plasmonic mode index change in MIM waveguide:

$\Delta n = 0.1$ at λ_0=800nm in 100 nm wide Au/SiO_2/ITO/Au MIM waveguide (from full field simulation)

E. Feigenbaum, K.A. Diest, and H.A. Atwater, *Nano Letters* 10, 2111 (2010).

The Search for New Low Loss Plasmonic Materials



- **Plasmonic device performance presently limited by metallic losses in noble metals such as Au and Ag**
- **Search for new plasmonic materials should be expanded to those with slightly lower carrier density and high mobilities**
- **Current focus is on conducting oxides and semimetals such as graphene.**

A. Boltasseva and H.A. Atwater, **Science**, **331**, pp 291–292 (2011).

Complex Nanophotonics

AFOSR-MURI 2009: Robust and Complex On-Chip Nanophotonics

Prof Shanhui Fan, Stanford, PI, team lead

Motivation:

•Most nanophotonic structures are fairly regular

•In general, no intrinsic reason to prefer regular structures

•Incorporating optical devices on chip is of crucial importance for next generation computing.

• Optics on-chip offers much lower energy consumption, lower heat dissipation, and higher information capacity compared with electronic devices

There is increasing need to develop optical structures that are more compact, that consumes less power, and that delivers novel information processing functionalities.

Objective:

- Achieve fundamental advances for understanding, designing, optimizing and applying complex non-periodic nanophotonic structures

- Solve some of most important chip-scale photonics challenge including compact and robust components for wavelength division multiplexing, multi-spectral sensing, photovoltaics, optical switching and low-loss nano-scale localization of light.

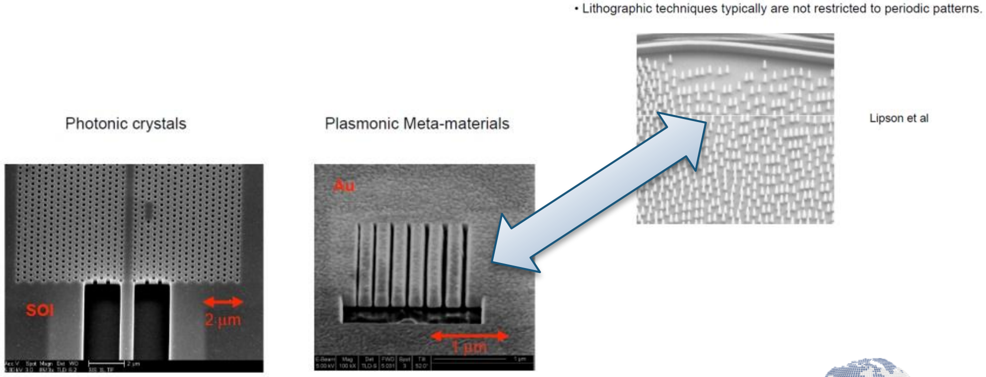
Explore and exploit the enormous degrees of freedom on-chip:

-Typical optical design specifies only a dozen of parameters

-From a fabrication point of view, there is no intrinsic reason to prefer such regular structures

-Single spatial degree of freedom on-chip

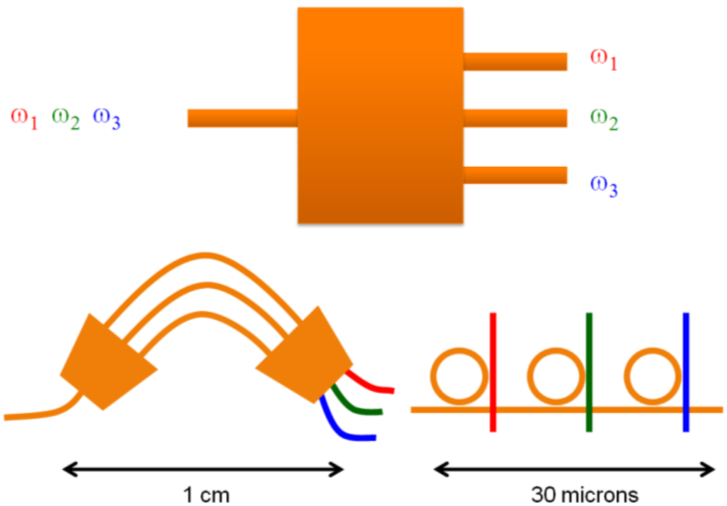
-Numbers of degrees of freedom for a $1mm^2$ chip area



AFOSR-MURI 2009:
Robust and Complex On-Chip Nanophotonics

WDM Filter Design

Towards ultra-compact WDM filters



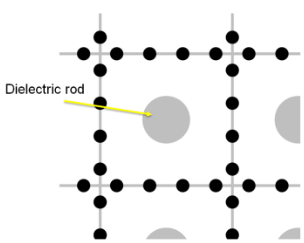
Developments of DtN Method

Development of "Conventional" Numerical Method

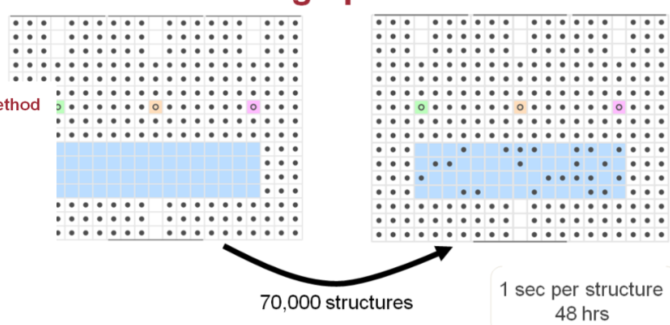
Dynamic photonic structures

Design process

The Dirichlet-to-Neumann (DtN) method

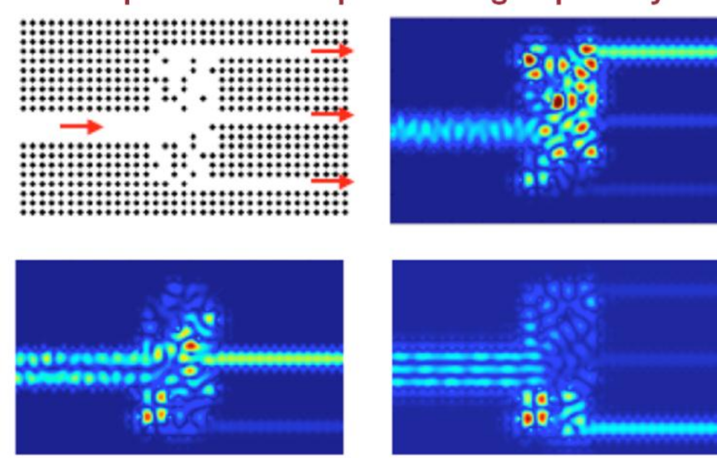


Store the field only on unit cell edges



•Eliminate reflection at the resonant frequencies.
• Each unit cell described by a very small matrix.
• Very efficient computation of DOS in photonic crystals (About two orders of magnitude speed up compared with conventional method).

Nonperiodic structure enables novel on-chip information processing capability

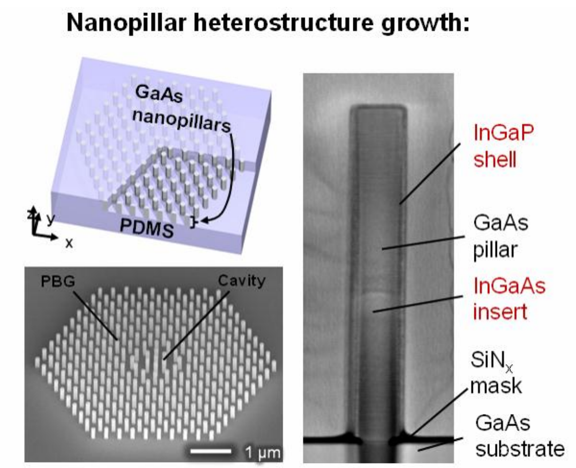


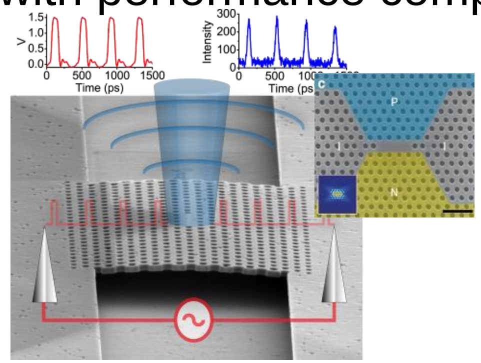
•Develop the fundamental science and the enabling capability to exploit on-chip complex and non-periodic nanophotonic structures.

A functional but non-intuitive device

Nanolasers & Nanosources: low power, low threshold, fast

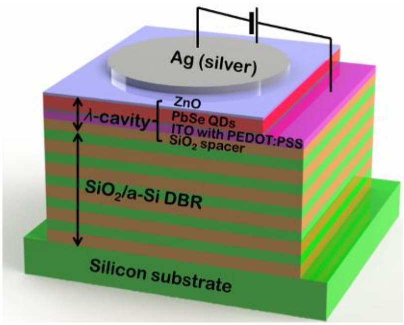
Bottom-up Photonic Crystal Lasers & Nanopillar Heterostructures and Optical Cavities, <u>Diana Huffaker, UCLA</u>: The combination of 3-D engineered heterostructures and high-Q cavities results in low-threshold, room temperature, continuous wave lasing. With at threshold power density of 75 W/cm2, this represents the first nanowire or nanopillar based laser with performance comparable to planar grown devices.





Ultrafast direct modulation of a single mode photonic crystal LED, <u>Jelena Vuckovic, Stanford</u>: demo'd ultrafast nanoscale LED orders of magnitude lower in power consumption than today's laser-based systems & able to transmit data at 10 billion bits per second..

Electrically Injected Room Temperature PbSe QD Laser on (001) Silicon, <u>P. Bhattacharya, Univ of Mich</u>



Light Generation Nanodevice - Electrically Controlled Nonlinear Generation of Light with Plasmonics: electric-field-induced second harmonic light generation, **<u>M. Brongersma, Stanford</u>**

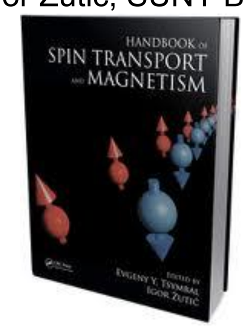
DCT on Reconfigurable Materials for Cellular Electronic and Photonic Arrays

Goal: Investigate promising novel electronic materials & nano-structures having potential for real-time, dynamically-large electrical & optical property tuning.

Approach: Atomistic modeling, mat’l synthesis, mat’l & device characterization to find the chemical and physical factors controlling mat’l parameter response to device scale

1) **electric fields,**
2) **magnetic field,**
3) **temperature, and**
4) **mechanical stressing,**

Igor Zutić, SUNY-B



Funding start: FY08

FLTC Links: 2,3,4,5,6,7,& 8 / Appl’s e.g.

Physical Properties

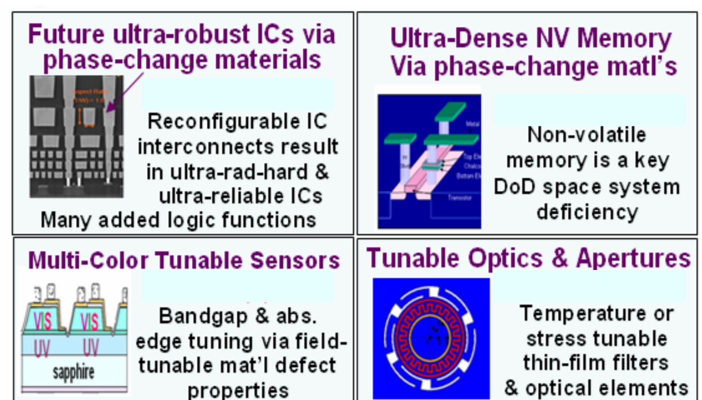
- **optical abs. edge (λ_{cutoff})**
- **electrical conductivity (σ)**
- **optical abs. coeff (α)**
- **index of refraction (n)**

Matl’s/Concepts for Study

- **defect-controlled bandgap tuning**
- **temperature tunable thin-films**
- **large ΔR phase-change matl’s**
- **novel matl’s for tunable apertures**

Cell Array Architecture

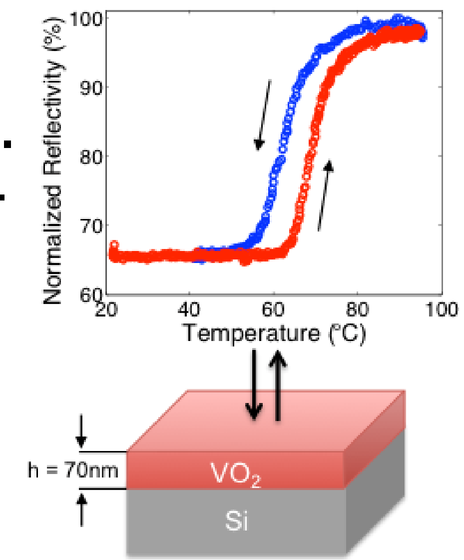
- **Optimized for cell design**
- **Optimized for specialized function**

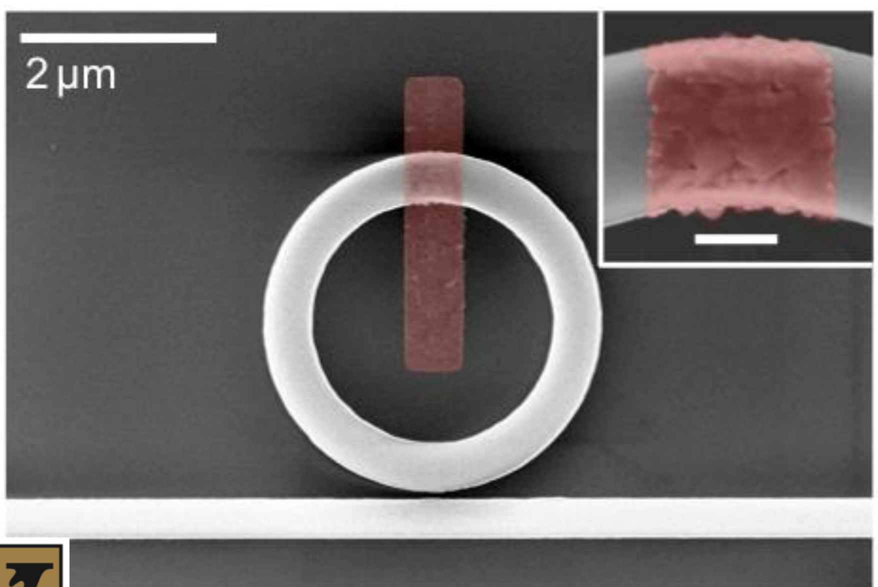


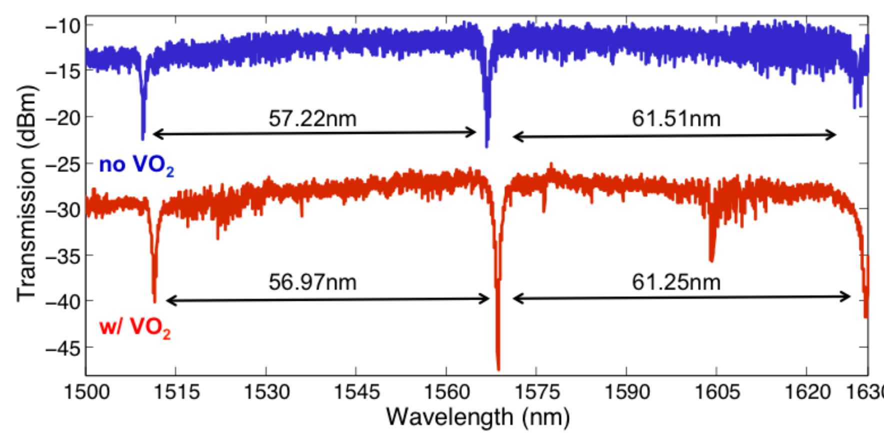
Photothermal Modulation of Ultra-compact Hybrid Si-VO_2 Ring Resonators

Sharon M. Weiss & Richard. F. Haglund, Jr., Vanderbilt

- Utilize semiconductor-to-metal transistion (SMT) of VO_2 for switching.
- Dramatic change in refractive index (~3.25 to 1.96) in near-IR.
- SMT can be triggered thermally, by an electric field, or by all-optical excitation (<100fs).
- Device: ~0.28μm² active area of VO_2 on a low-mode volume, ~1μm³, silicon ring resonator with 1.5μm radius. Large FSR (~60nm), modest Q-factor (~10³) for reduced cavity lifetimes (<1ps)





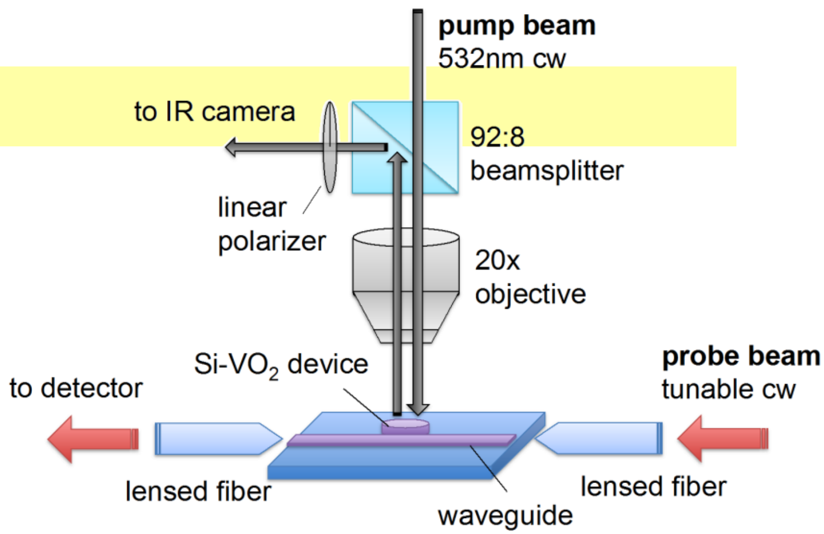


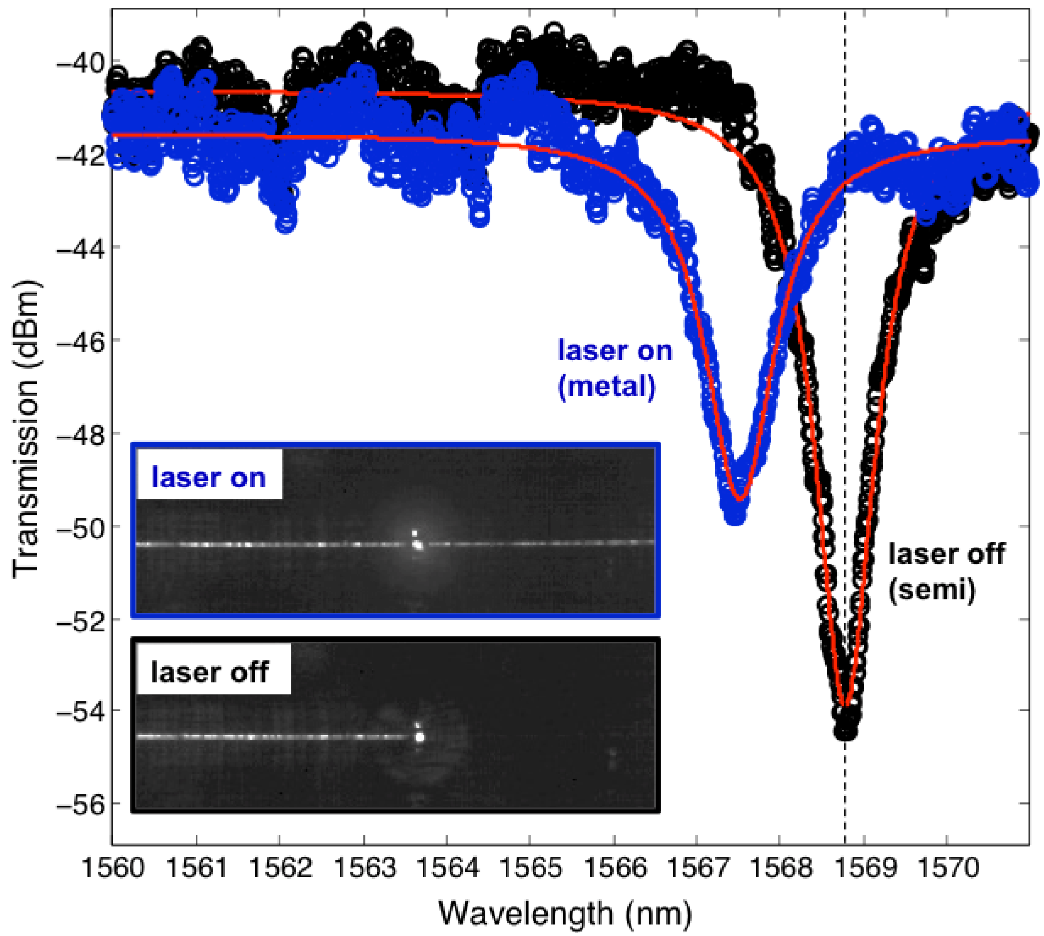
VANDERBILT

PHOTOTHERMAL MODULATION OF ULTRA-COMPACT HYBRID SI-VO_2 RING RESONATORS

Sharon M. Weiss, & Richard. F. Haglund, Jr., Vanderbilt (cont)

- Switching demonstrated using localized photothermal excitation by continuous 532nm laser illumination.
- Transition to metallic state reduces effective index dramatically:
  - → Δλ = –1.26nm resonance shift
  - → >10dB optical modulation



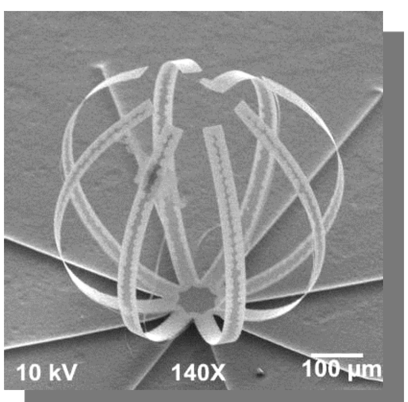


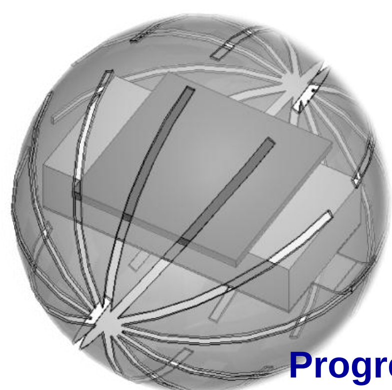
“Programmable Reconfigurable Sensors” Si-SiO_2 Micro-shells for Micro-robots

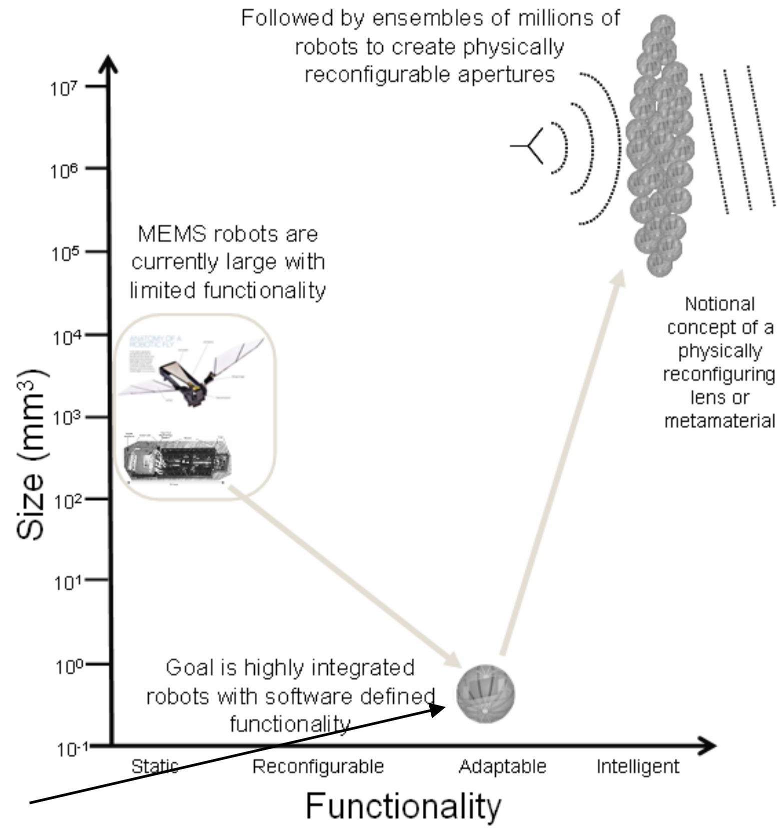
LRIR – RYHI , WPAFB – Dr. Vasilyev

Objective: Create a material capable of <u>dynamically</u> changing shape and density to form three dimensional apertures or meta-materials

One can achieve this goal using ensembles of large numbers (>10^6) of sub-mm^3 mRobots.







Progress:
- developed a process for fabricating the physical structure required for sub-cubic mm autonomous robotic systems
-currently integrating CMOS circuitry (thin film solar cell and IC) into these structures.

- AFRL will be the first to integrate structure, programmability, and functionality at the sub-mm3 scale.

Autonomous Reconfigurable Interconnect Cell (ARIC)

AF STTR AF11-BT26 Phase-I: Cellular Elements For Ensemble Based Programmable Matter

Objective: Design and development of an autonomous reconfigurable interconnect cell (ARIC)-based programmable matter to address AFRL's requirement for a miniaturized cellular element for ensemble based programmable matter.

Approach: Reconfigurable antennas (Fig.1) , power harvesting (Fig.2) and adaptive wiring concepts (Fig.3), and coherently fuse the salient features of these concepts

Key Personnel:

Dr. Sameer Hemmady, (TechFlow) & Dr. Marios Pattichis, (UNM)

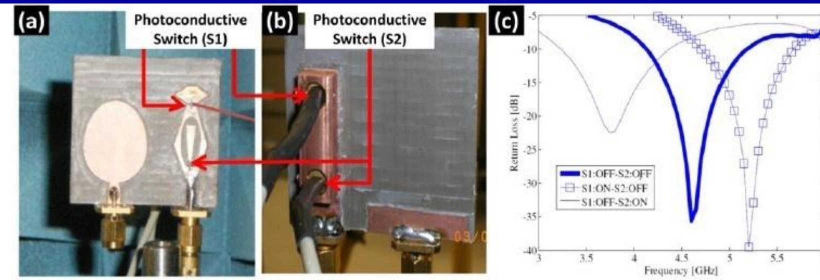


Fig.1: The TechFlow teams' previously demonstrated integrated Optically Pumped Reconfigurable Antenna Technology (iOPRAS).

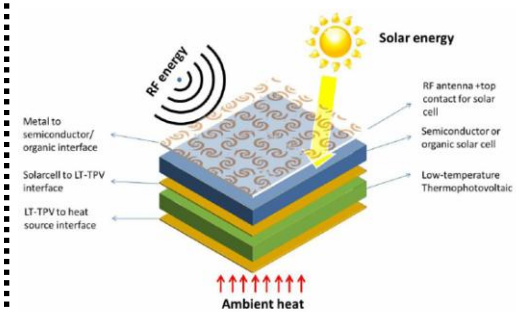
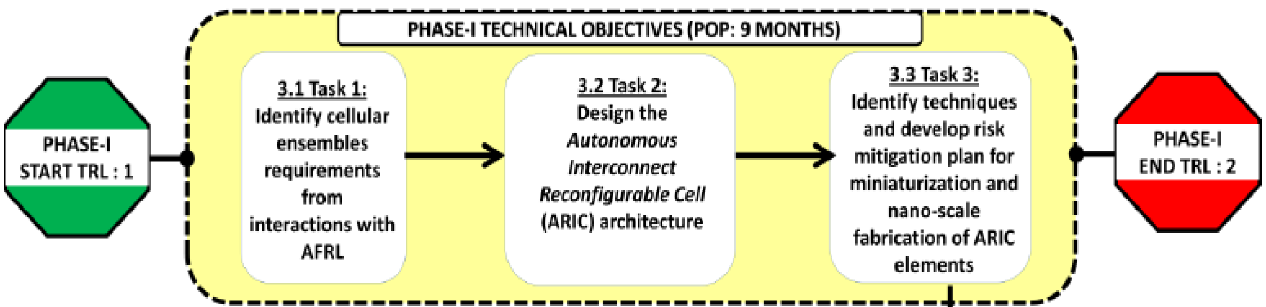


Fig. 2: The TechFlow teams' proposed power harvesting core.

Fig.3: The TechFlow teams' previously demonstrated adaptive wiring concept



Relevance: Swarms of small, miniaturized space-based platforms and satellite constellations equipped with ARIC-based self-powered reconfigurable optical and RF sensors can be interconnected to form scalable grids.

TECHFLOW THE UNIVERSITY of NEW MEXICO

AFRL

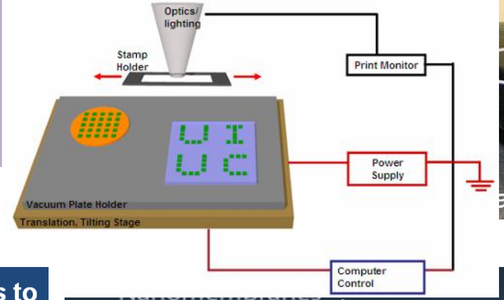
Nanomanufacturing - Photonics & Nanomaterials

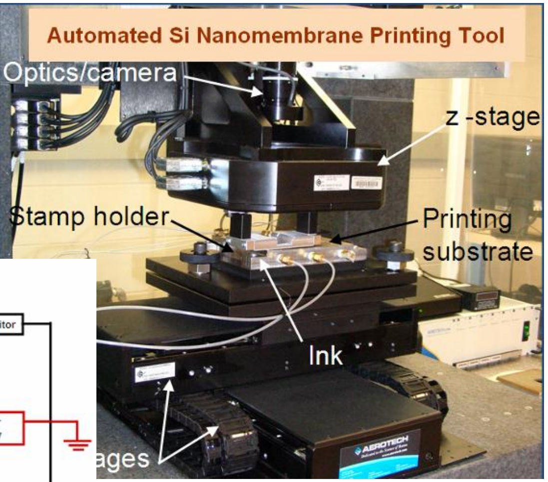
Texas-led MURI-Center for Silicon Nano-Membranes – PI Prof R. Chen

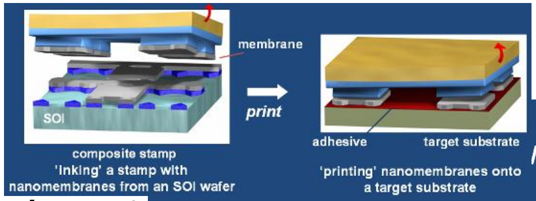
Scientific novelty and Uniqueness:

- **Nanomembrane lithography to form 3D well-aligned silicon nanomembranes**
- **Ultracompact structure provides large steering angles in both azimuth and elevation directions for Optical Phased Array (OPA)**
- **Slow photon in PCW provides a group index above 100 and provides tunable delay time suitable for phased array antenna applications**

Transfer Printing Tool Schematic - UIUC

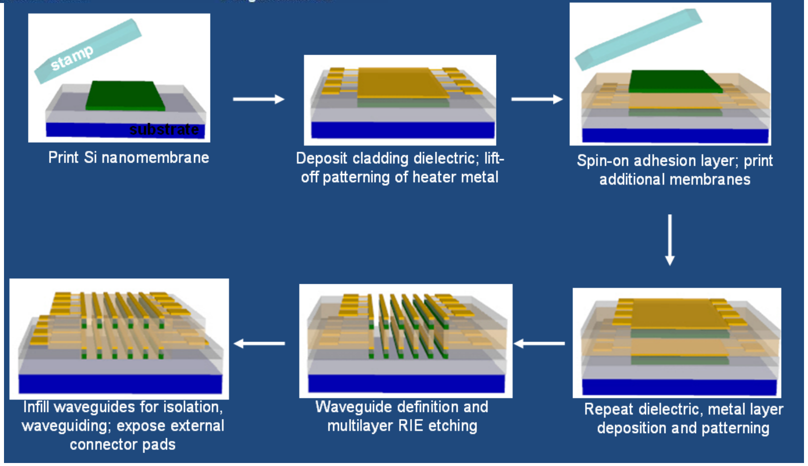


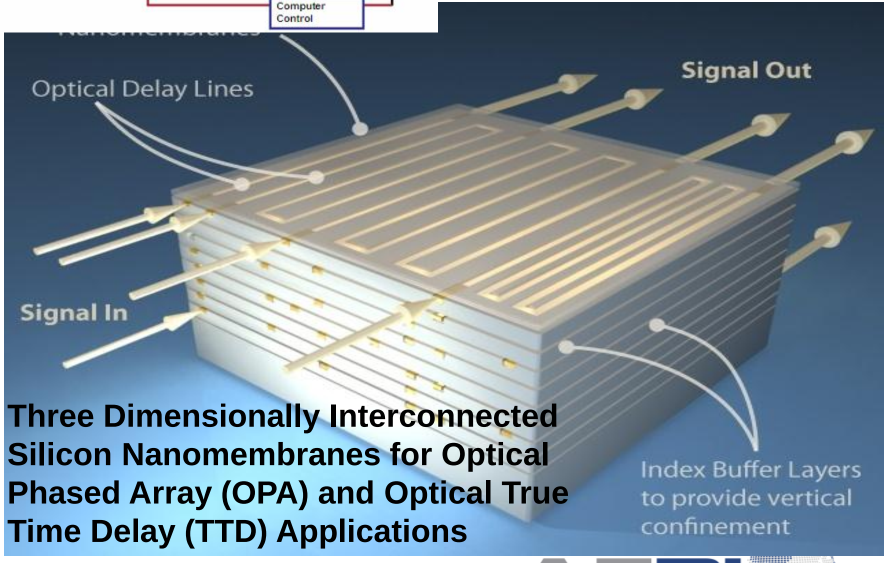




Stacked Nanomembranes to Waveguides and Functional OPAs

Printing Process for Manipulating Si Nanomembranes





Three Dimensionally Interconnected Silicon Nanomembranes for Optical Phased Array (OPA) and Optical True Time Delay (TTD) Applications

Nanomanufacturing

Mechanics of Microtransfer Printing

Fundamental knowledge of nano-membranes, exportable to other materials classes

Improving Retrieval Through Stamp Geometry

MURI on Group IV Nanomembranes

Prof Max Lagally, UWI lead, w/ K. Turner, J. Rogers

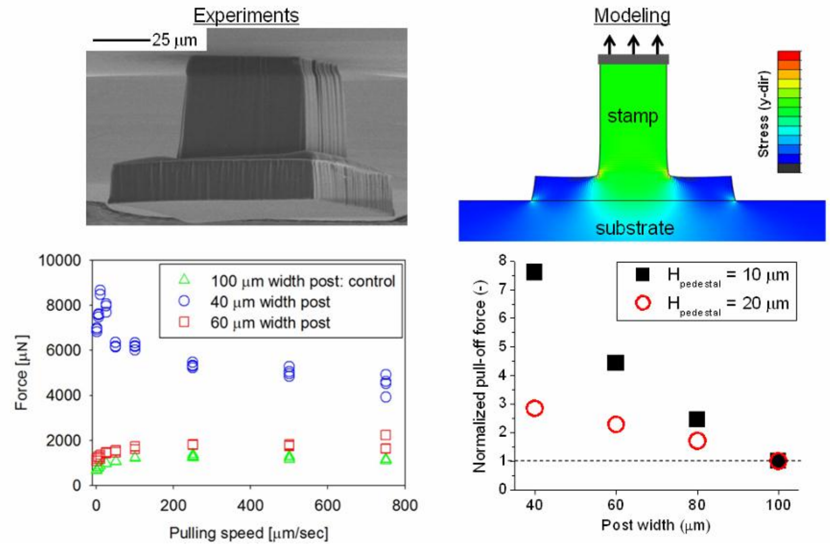
Characterizing and Tailoring Adhesion in SiNM Systems

Membrane Transfer and Integration:

Wet release and transfer
Soft-stamp dry transfer printing
Wafer bonding and transfer

Key Factors: Elastic properties, Interface adhesion, SiNM thickness, Surface structuring, Membrane shape, Direction of applied load

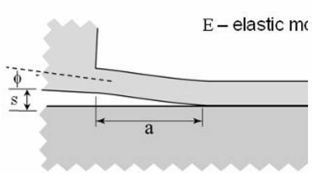
Model-Experiment Comparison

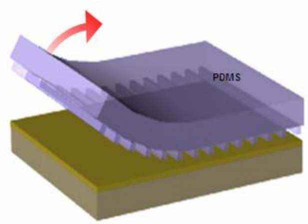


Characterizing Adhesion of Si Membranes

Measurements of adhesion

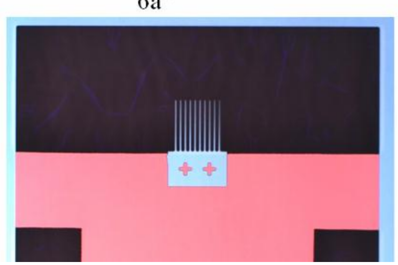
- Si-Si interfaces (native SiO_2)
- Examine role of environment and surface preparation at RT



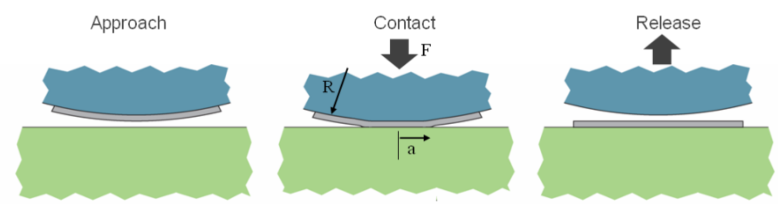


$$G = \frac{Eh^3}{6a^4}(\phi a - 3s)^2$$

Structures fabricated from SOI



Contact and Release in Load Controlled Processes



Interface will bond when: $G < W_A$ (work of adhesion)

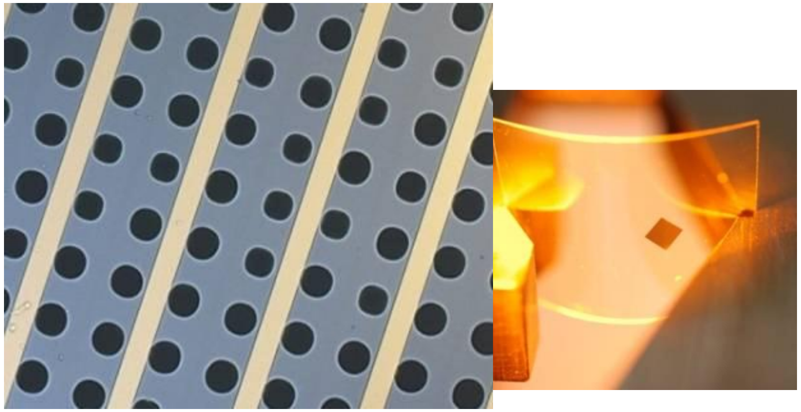
Interface will separate when: $G > W_S$ (work of separation)

Accurate values of W_A and W_S are crucial in process modeling

Nanomanufacturing - Photonics & Nanomaterials

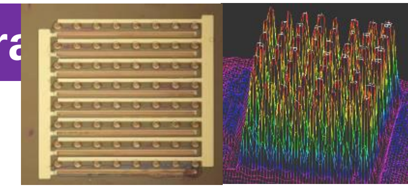
NM Photonics Major Research Highlights (III-V/Si NM Flexible Photonics)

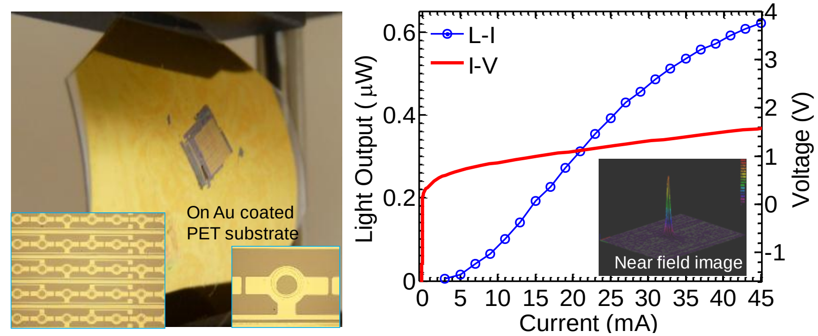
Frame-assisted membrane transfer (FAMT) process



- IEEE Group IV Photonics 2009;
- US patent pending

Flexible InP NM LED arra

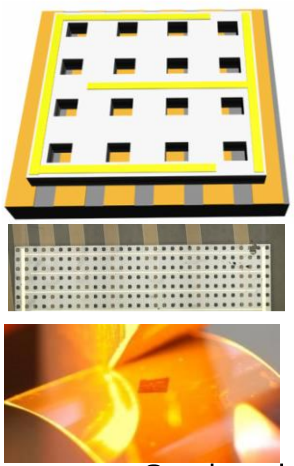




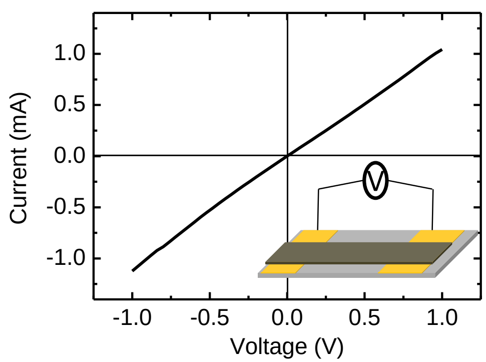
(a) (b)

- IEEE Photonics Society Annual Meeting 2010.

Anneal-Free Stacked Electrodes

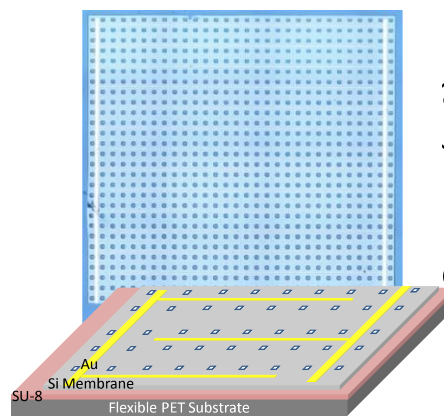


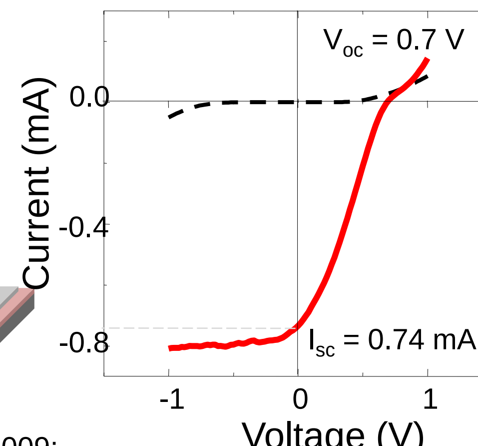
Annealing free InP-ITO electrodes on flexible substrates



Semicond. Sci. Tech 2011, IoP Select; Labtalk

Large area flexible photodetectors and solar cells





- IEEE Group IV Photonics 2009;
- W. Yang et al., Appl. Phys. Lett. 96, 121107 (2010).

W. D. Zhou,UTx-Arlington and Z. Ma UWI-Madison – MURI PI M. Lagally

Lasers on Silicon for Silicon Photonics

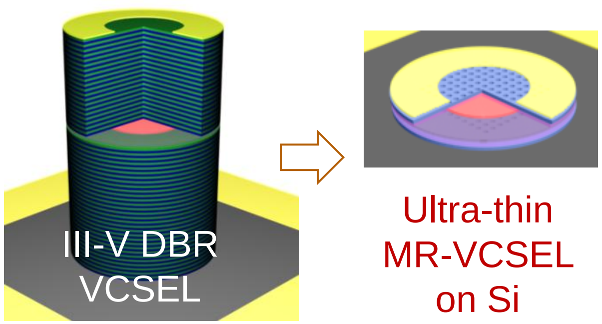
AFOSR STTR Phase I/II (Semerane, Inc.)

Motivation:

Coherent Light Source Need for Si photonics

Objective:

A practical laser on Si via nanomembrane transfer printing



MR-VCSEL: Membrane-Reflector Vertical-Cavity Surface-Emitting Laser

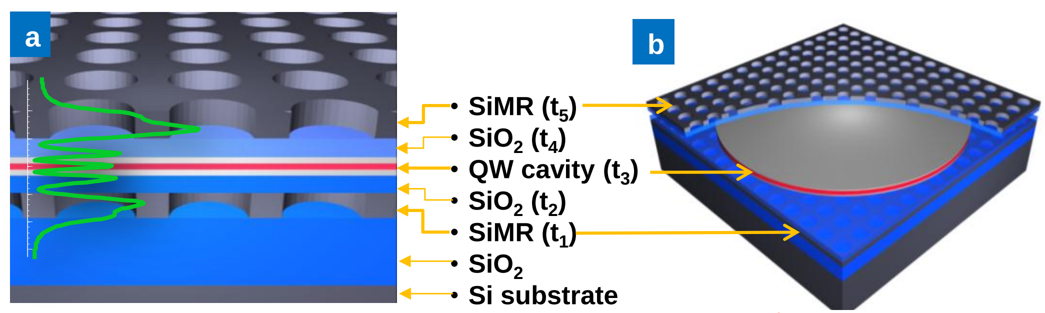
Accomplishments

- First demonstration of optically pumped lasers on Si based on nanomembrane transfer printing (patent pending and licensed to Semerane)

Approaches:

- Multi-layer nanomembrane transfer printing for III-V/Si heterogeneous integration
- Single layer Si NM photonic crystal Fano membrane reflector (MR) replaces conventional DBR.

Application Example:
3D photonic/Electronic integration, optical interconnect, and WDM on Si.



Semerane PI: Dr. Hongjun Yang
University PIs:
Prof. Z. Ma, U. Wisconsin-Madison
Prof. W. Zhou, U. Texas at Arlington

Partial support: MURI Program on Nanomembranes

“to be published in Mar 2012"

Semerane Inc.

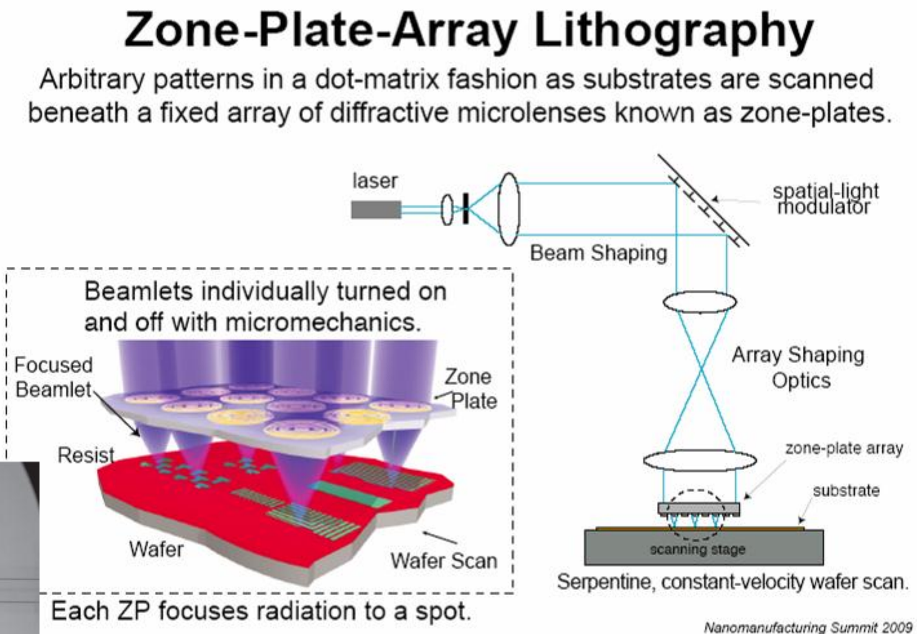
Nanomanufacturing & Photonics

Flexible Micro- and Nanopatterning Tool for Photonics

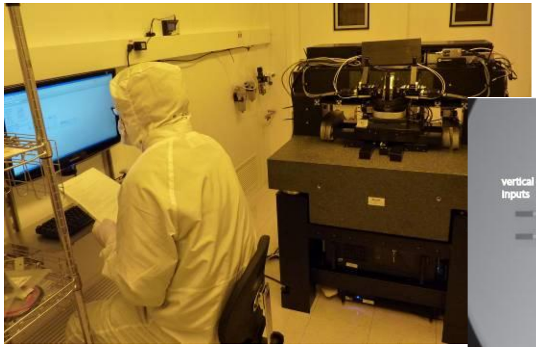
STTR Topic: Nanopatterning; OSD10-T006

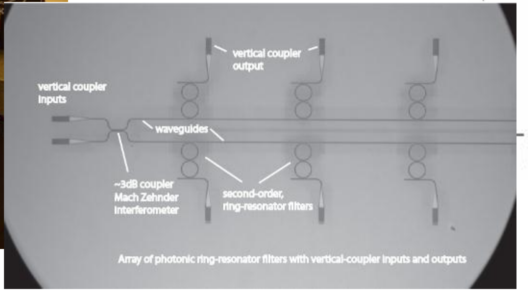
PI: Henry I. Smith, LumArray, MA & Co-PI: R. Menon, Univ. Utah

- **Objective: Achieve lithographic resolution, accuracy, fidelity and flexibility needed for photonics (r**



- 1000 lenses operate in parallel for high throughput
- Correction in software =>spatial coherence & precision
- Full wafer patterning





Array of ring-resonator filters coupled to a waveguide written at LumArray on the ZP-150 alpha maskless photolithography system

DoD impact: A lithography tool for photonics research, development and low-volume manufacturing as well as custom DoD electronics. Tool provides long-range spatial-phase coherence essential to high performance photonics.

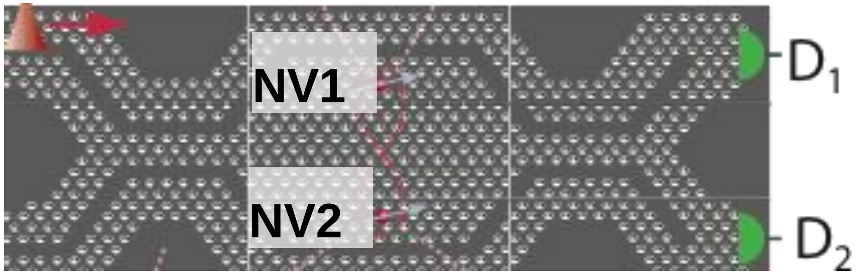
Quantum Computing

Selim Sharihar – NWU: **Optically Controlled Distributed Quantum Computing Using Atomic Ensembles as Qubits**

Duncan Steel – Univ of Mich: **Working Beyond Moore's Limit: Coherent Nonlinear Optical Control of Individual and Coupled Single Electron Doped Quantum Dots**

Stefan Preble – Rochester IT: building blocks for quantum computers- fully quantum mechanical model of the interactions of individual photons in dynamically tuned micro-resonator circuits

Dirk Englund – Columbia (PECASE): **Quantum Optics in Diamond Nanophotonic Chips - Development of an efficient solid state spin-photon interface**



Leuenberger – UCF: **Quantum Network inside Photonic Crystal (PC) made of Quantum Dots (QDs) in Nanocavities**

Highlight: single-photon emission from single quantum dot (QD)

Our modified relativistic Lagrangian:

modification using self-dual tensor:

$$\mathcal{L}_{\text{El-Ph},A_{\text{Ext}}} = \bar{\psi}\left(\not{p} - m_0 c\right)\psi - \frac{e}{c}\bar{\psi}\left(\not{A} + \not{A}_{Ext}\right)\psi - \frac{1}{8}\mathfrak{G}_{\mu\nu}\mathfrak{G}^{\mu\nu}$$

which leads to electron-photon interaction and free-photon Dirac-like equation:

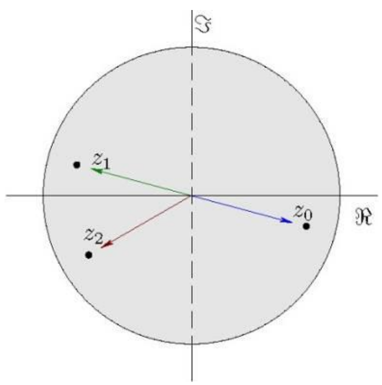
$$i\hbar\dot{c}_a(t) = \left(-i\vec{\Psi}^{(+)}_{\gamma,\sigma_+} + i\vec{\Psi}^{\dagger(+)}_{\gamma,\sigma_-}\right)_{,b} e^{i\omega_\sigma t}\cdot\vec{\wp}_{ba}$$

$$i\hbar\sum_{\vec{k},\sigma_\lambda}\dot{c}_{b,\vec{k},\sigma_\lambda}(t) = \left(-i\vec{\Psi}^{(-)}_{\gamma,\sigma_+} + i\vec{\Psi}^{\dagger(-)}_{\gamma,\sigma_-}\right)_{,a} e^{-i\omega_\sigma t}\cdot\vec{\wp}_{ab}$$

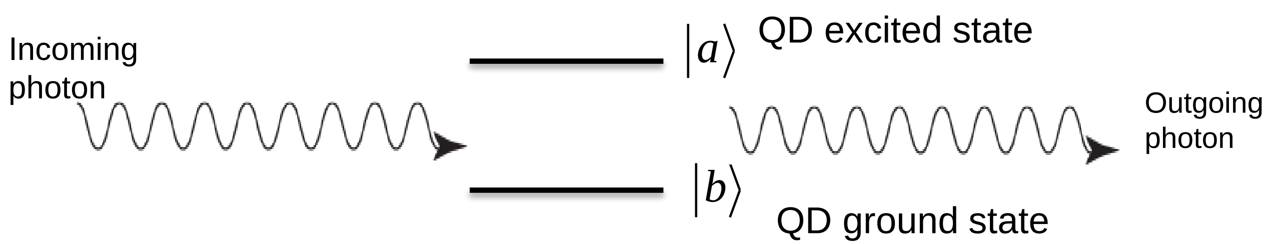
$$\left[\frac{i\hbar}{c}\partial_t\begin{pmatrix} 0 & I \\ -I & 0 \end{pmatrix} - \frac{\hbar}{i}\partial_k\begin{pmatrix} 0 & \sigma_k^{(3)} \\ \sigma_k^{(3)} & 0 \end{pmatrix}\right]\begin{pmatrix} \vec{F}_+ \\ \vec{F}_- \end{pmatrix} = 0$$

Equation for excited QD state $|a\rangle$ going beyond Weisskopf-Wigner theory:

$$c_a^{(3)} + 3i\omega_\sigma c_a^{(2)} - \left(3\omega_\sigma^2 + i\frac{\hbar}{\lambda}\right)c_a^{(1)} - i\omega_\sigma^3 c_a = -\frac{1}{\lambda}\left[-i\vec{\Psi}^{(+)}_{\gamma,+,b}\left(\vec{x}_0\right) + i\vec{\Psi}^{\dagger(+)}_{\gamma,-,b}\left(\vec{x}_0\right)\right]\cdot\vec{\wp}_{ba}e^{i\omega_\sigma t}$$



$$z_{n'} = z_n + i\omega_\sigma$$



Solution determined by 3 characteristic roots, corresponding to eigenenergies of 3-dimensional system:

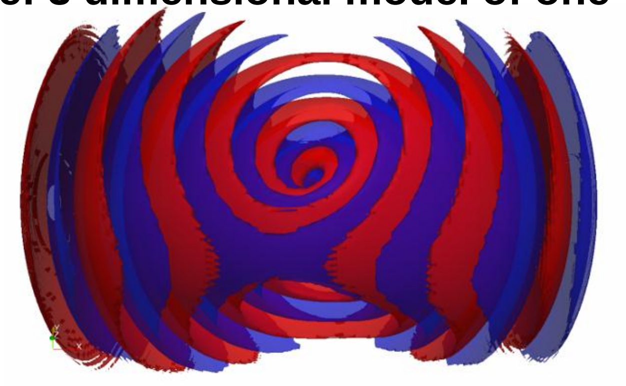
$$t \to -\infty \qquad t = 0 \qquad t \to \infty$$

$$|1_{in}\rangle|b\rangle \to |0\rangle|a\rangle \to |1_{out}\rangle|b\rangle$$

Highlight: single-photon emission from single quantum dot (QD)

- **Coded Quantum-field theoretical FDTD solver using fully parallelized MPI C++.**
- **$\Rightarrow$ 3D visualization of emitted single-photon field using isosurfaces.**
- **Example: 3 dimensional model of one QD at 91.74 attoseconds:**

$\Re\left\{\vec{\Psi}^{(+)}_{\gamma,+,b}\right\}\cdot\hat{y}$



$\Re\left\{\vec{\Psi}^{(+)}_{\gamma,+,b}\right\}\cdot\hat{x}$

- **1st important result:** Near-field revival phenomena during single-photon emission lead to low-order polynomial decay, instead of usual exponential decay of the population of excited QD state $|a\rangle$. Reason: single photon gets reabsorbed and reemitted by QD during single-photon emission process.

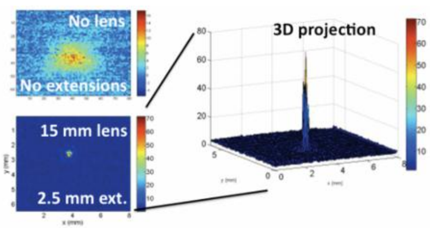
- **2nd important result:** High-frequency near-field oscillations are visible. They are due to initial localization of the energy of the single photon to the QD region, resulting in an energy uncertainty that can be explained using the Heisenberg uncertainty principle.

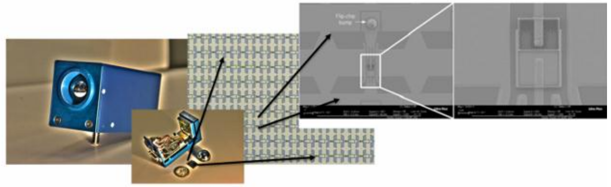
- In the future these phenomena could be experimentally verified by Dirk Englund at Columbia University (PECASE)

Results & Transitions

People, Research, Products – Government, Academia, Industry

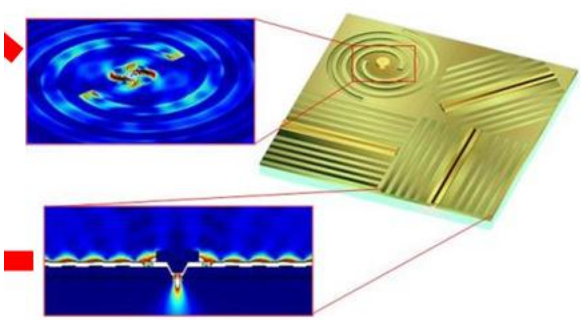
Traycer Diagnostic Inc, AFOSR Phase 2 STTR terahertz detector program – wins $3M state of Ohio funds + $1M AFRL





EM Photonics Phase 1 & 2 , Scalable Reconfigurable Chip-Scale Routing Architecture, to spin-off Lumilant, with subsequent NAVAIR, DARPA NEW-HIP, AF, MDA, & TELECOM and DATACOM vendors funding for WDM Router to JSF-F35, Satellite Optical Backplane (KAFB), photonic true time delay & coherent communication systems

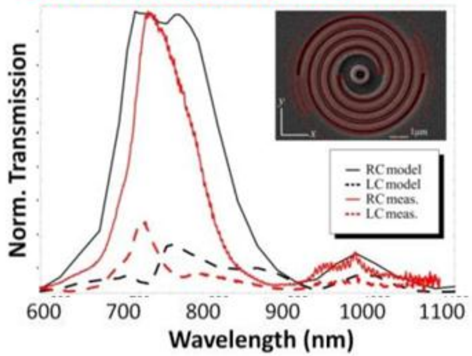
Plasmonic Cavity Spectroscopic Polarimeter, ITN Energy Systems, Inc. & Colorado School of Mines - Full Stokes vector focal plane array & Photodiode integration; dialogue with NRO & proposal submission



Plasmonic Cavity Spectroscopic Polarimeter, FA9550-10-C-0024

Russell Hollingsworth – ITN Energy Systems, Inc. P. David Flammer – Colorado School of Mines

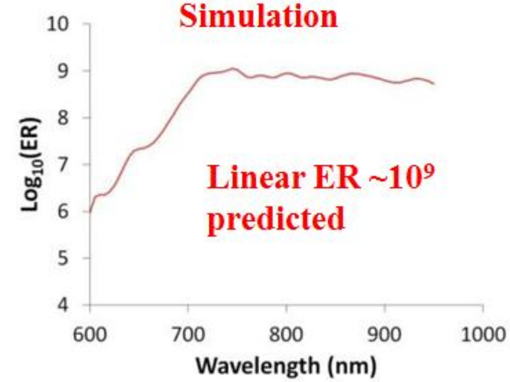
Measurement vs. simulation

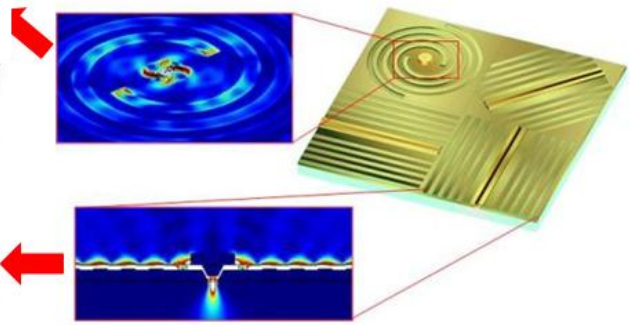


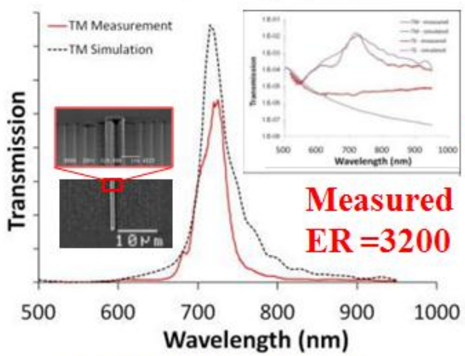
Plasmonic micropolarizing color filters

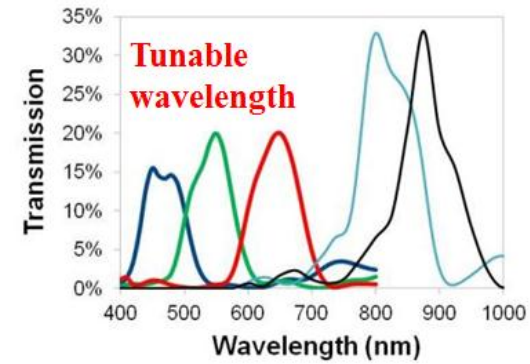
- First easily fabricated circular micropolarizer demonstrated
- Excellent measurement – FEM simulation agreement
- Visible to IR operation

Simulation



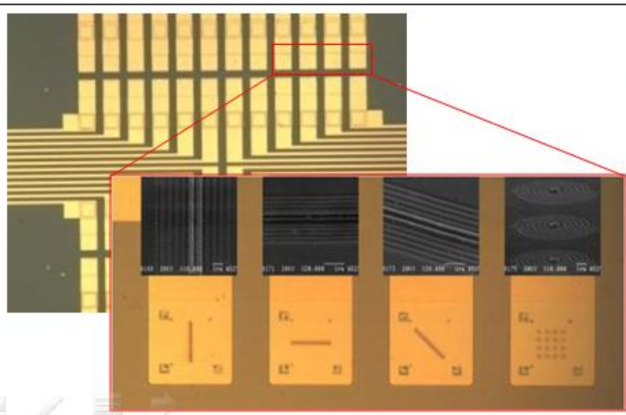






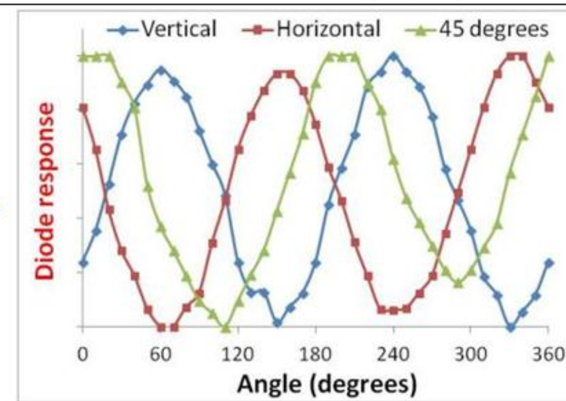
Full Stokes vector focal plane array

- Simultaneous, simple fabrication of linear and circular sensitive filters



Photodiode integration

- Monolithic integration on focal plane arrays using standard processes
- Wavelength & polarization tunable on pixel by pixel basis
- Collection area much larger than transmission spot allows small, low noise, fast detectors

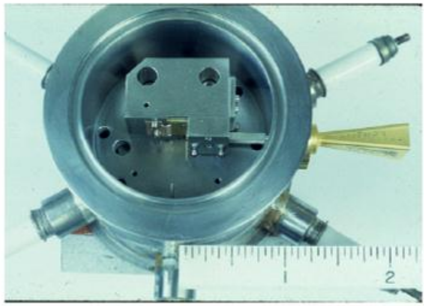


Results & Transitions (cont)

Nanomembrane Research, Prof Robert Blick, Univ of WI, Application as Detector for Protein Masses in collaboration with Prospero Biosciences - acquisitionof professional Mass Spectrometer (Voyager STR 510) ($1M NIH grant, $0.43M UWI grant)

Univ of Delaware, Prof Prather, Conformal-shared Apertures for Air Force Platforms – CAAP – Mar 2011 – 36 months - $1.05M, meta-material devices and integration process to demo RF Photonic Systems

Terahertz Device Corporation, THz related STTR Topics, Phase 2 & separate Ph1 - THzDCorp develops and sells infrared LED product line, based on III-V semiconductor nanostructures, covers wavelengths from about 3 μm to beyond 20 μm; plus BWO product line, relying on microfabricated slow-wave circuits and electron beam innovations, covers frequencies from about 200 GHz to 1.8 THz http://thzdc.com/index.html

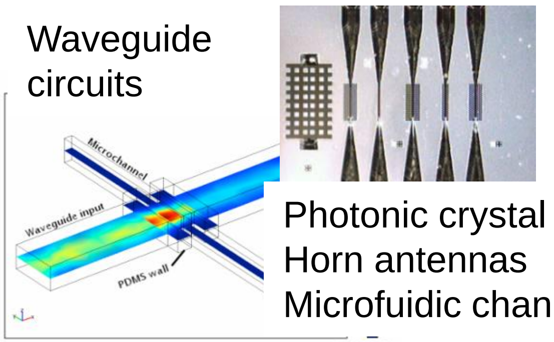


Charles Reyner - UCLA to AFRL/RY transition - SMART program

Terahertz Waveguide Laser Circuits to Far-IR LEDs: Technology Accumulation and Transfer

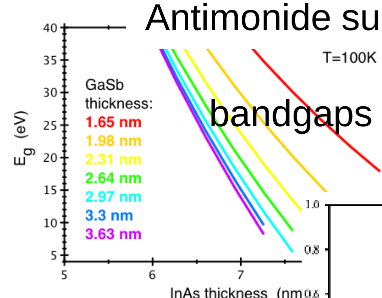
Materials, devices, circuits, architecture: STTR (2002 – 2006) – antimonide and arsenide gain media, MBE growth, photonic crystal WG fabrication, laser engineering

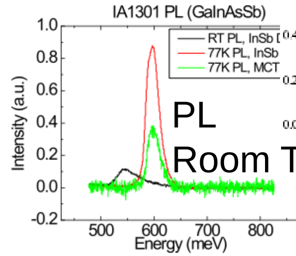
Waveguide circuits

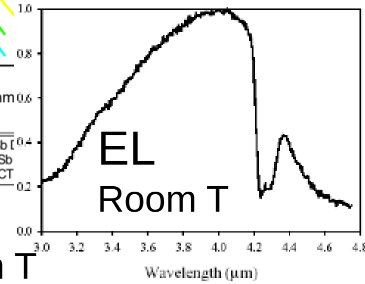


Photonic crystal WG
Horn antennas
Microfuidic channels

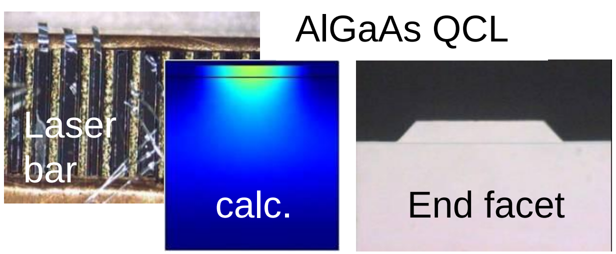
Antimonide superlattices







AlGaAs QCL



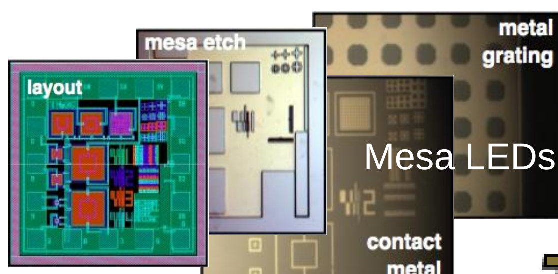
M. S. Miller

T. Boggess
T. Hasenberg
J. Prineas
M. Flattè

J. Hesler

C. Pryor
R. Simes
M. S. Miller

LED development by THzDC:
long wavelength 4 – 30 µm (2010)



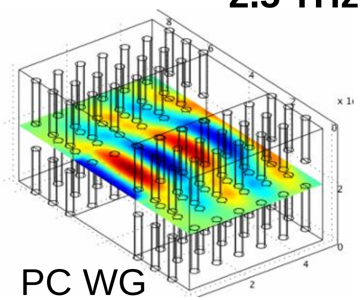
Commercialization status:
Accepting LED pre-orders (samples in fall 2011)
Sales@thzdc.com

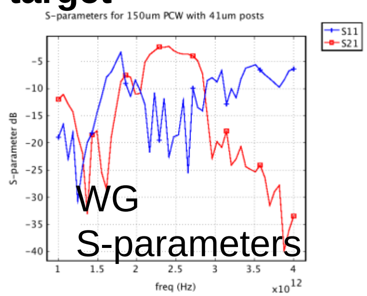
THzDC
Terahertz Device Corporation

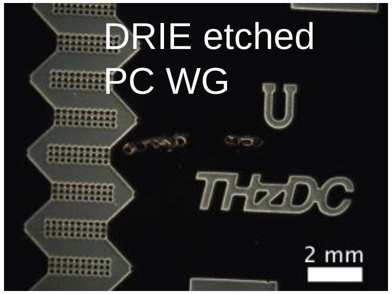
Microfabricated Terahertz Backward Wave Oscillators: Technology Nucleation to Transfer

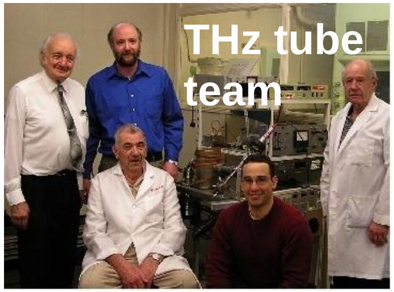
Photonic crystal slow-wave circuits: STTR (2006) feasibility test, fabrication studies

2.5 THz target









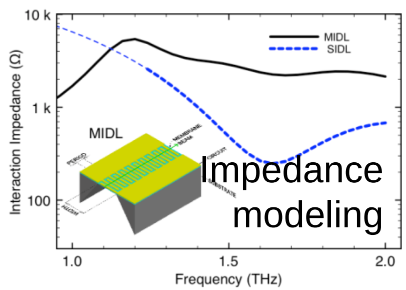
THE UNIVERSITY OF UTAH

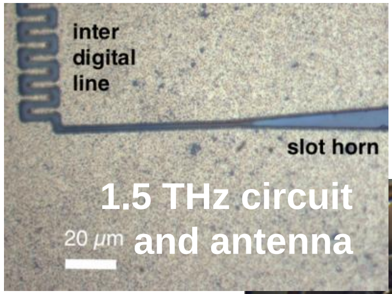
M. S. Miller
R. W. Grow

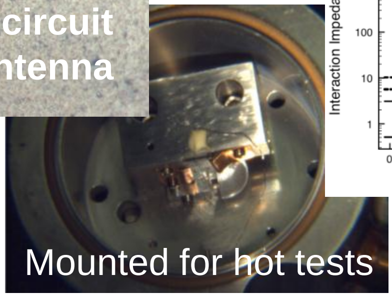
Scaling solutions – High-impedance circuits, electron beams, no magnets:

BWO Dissertation:
Everything scales
except the beam
(G. Oviedo Vela, 2010)

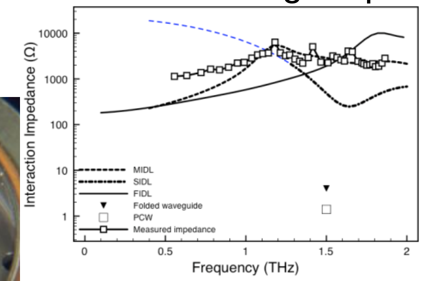
0.6 – 1.8 THz tuning







Impedance measured
while tuning output



More than one
octave tuning

New circuits and electron beams:

NSF SBIR (2011) for product development

Commercialization status:

Seeking partners, accepting pre-orders (2011)

Sales@thzdc.com

THzDC
Terahertz Device Corporation

AFRL

Other Organizations That Fund Related Work

<u>Terahertz Sources & Detectors</u> - limited funding from JIEDDO, DHS, DTRA, NSF; AFOSR individual investigator & signif STTR efforts (compact sources & detectors, optical approaches) [formerly AGED meetings, professional mtg support & attendance]

<u>Quantum Computing w/ Optical Methods</u> – funding by NSA, NSF, DOE (NNSA, OS), NIST, IARPA, ARO, ONR, DARPA; AFOSR efforts focused on optical/photonic approaches to QC [regular meetings of the NSTC Subpanel on QIS, OSTP lead]

<u>Reconfigurable Photonics and Electronics</u> (DCT) – limited, dispersed funding; AFOSR most significant and focused program - Investigating promising novel electronic materials & nano-structures having potential for real-time, dynamically-large electrical & optical & magnetic property tuning [annual meetings, AFRL/RV & RY major role]

<u>Nanophotonics</u> (Plasmonics, Photonic Crystals, Metamaterials), Nano-Probes & Novel Sensing – funding by NSF, DARPA, & limited by ARO (DARPA Agent). AFOSR had first national level program focused on nano-photonics; leading in funding chip scale plasmonics, photonic crystals, nano-antennas, nano-emitters & modulators. [Agency Reviews, National Academies input]

<u>Integrated Photonics</u>, Optical Components, Optical Buffer, Silicon Photonics – significant funding by DARPA, NSF. AFOSR has lead in silicon photonics, VCSELs, Q-Dot emitters, slow-light, waveguides, optical phased-arrays, developing III-V compound semiconductors. [Agency Reviews, NNI]

Optoelectronic Information Processing

Nanophotonics, Plasmonics, Integrated & Silicon Photonics

Demo'd first plasmonic all-optical modulator, plasmon enhanced semiconductor photodetector, plasmon laser, superlens, hyperlens, plasmonic solitons, slot waveguide, "Metasurface" collimator etc

AFOSR is the scientific leader in nanophotonics, nanoelectronics, nanomaterials and nanoenergetics – one of the lead agencies to the current OSTP Signature Initiatives "Nanoelectronics for 2020 and Beyond" and coordinating member to "Sustainable Nanomanufacturing"

FY11 Selected Awards/Prizes

-Sloan Fellowship & PECASE – Englund
- National Academy of Engineering & Lemelson-MIT Prize – John Rogers
- MRS Kavli Distinguished Lecturer in Nanoscience – Atwater
- Sackler Prize in Physics: S. Meier & M. Brongersma
- H. I. Romnes Fellowship from Univ of Wisconsin – Jack Ma
- numerous OSA, MRS, SPIE fellows

Close coordination within AFRL, DoD, and 26 federal agencies as NSET member to the National Nanotechnology Initiative (NNI) http://www.nano.gov/partners

Jennifer Dionne
Technology Review's TR35 list

"Oscar for Inventors," the Lemelson-MIT Prize, J. Rogers UICU

Integrated & Silicon Photonics - Engine for 21st Century Innovation

http://www.nano.gov/initiatives/government/signature

http://www.nano.gov/

Interactions - Program Trends

AFOSR PMs

RSE: Reinhardt, Weinstock, Curcic, Nachman

RSL: Bonneau, DeLong

RSA: C. Lee, L. Lee

RSPE: Lawal, E. Lee

AFRL – RY, RI, RX, RV, RW, 475th

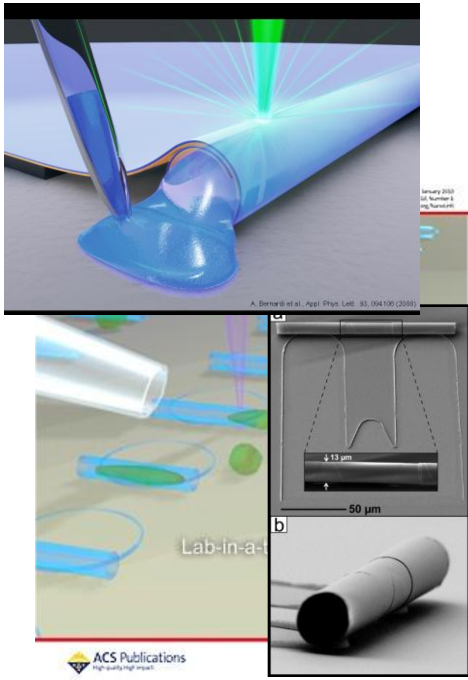
AFRL – HPC Resources

EOARD – Gavrielides, Gonglewski, Dudley

AOARD – Erstfeld, Jessen, Seo,Goretta

SOARD – Fillerup, Pokines

- Quantum Computing w/ Optical Methods QIS) →
- Reconfigurable Ph. & Optical Computing →
- Terahertz Sources & Detectors →
- Nanophotonics ↗
  - ---- Plasmonics, Nonlinear, MetaPhotonics
  - ---- Chip-scale, 3D, computation (logic)
- Nano-Probes ↘
- Integrated Photonics, Silicon Photonics ↗
- Nanofabrication (MURI, OSD & AFOSR STTR) ↘



In Memory: Prof H. John Caulfield

Conclusion & Vision

Program has driven the plasmonics, photonic bandgap, and silicon photonics invest by the Services

Key ideas:

Plasmonics
Bandgap engineering
Strain eng.
Index of refraction eng.
Dispersion eng.
Subwavelength - Operating beyond the diffraction limit
Nonlinear effects
Metamaterials/TrOptics /
Metasurfaces
Nanofabrication

Establish a shared, rapid, stable **shuttle process** for building high-complexity silicon electronic-photonic systems on chip, in a DOD-Trusted fabrication environment, following the MOSIS model

AFOSR in Wall Street Journal --> Optical Chips

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